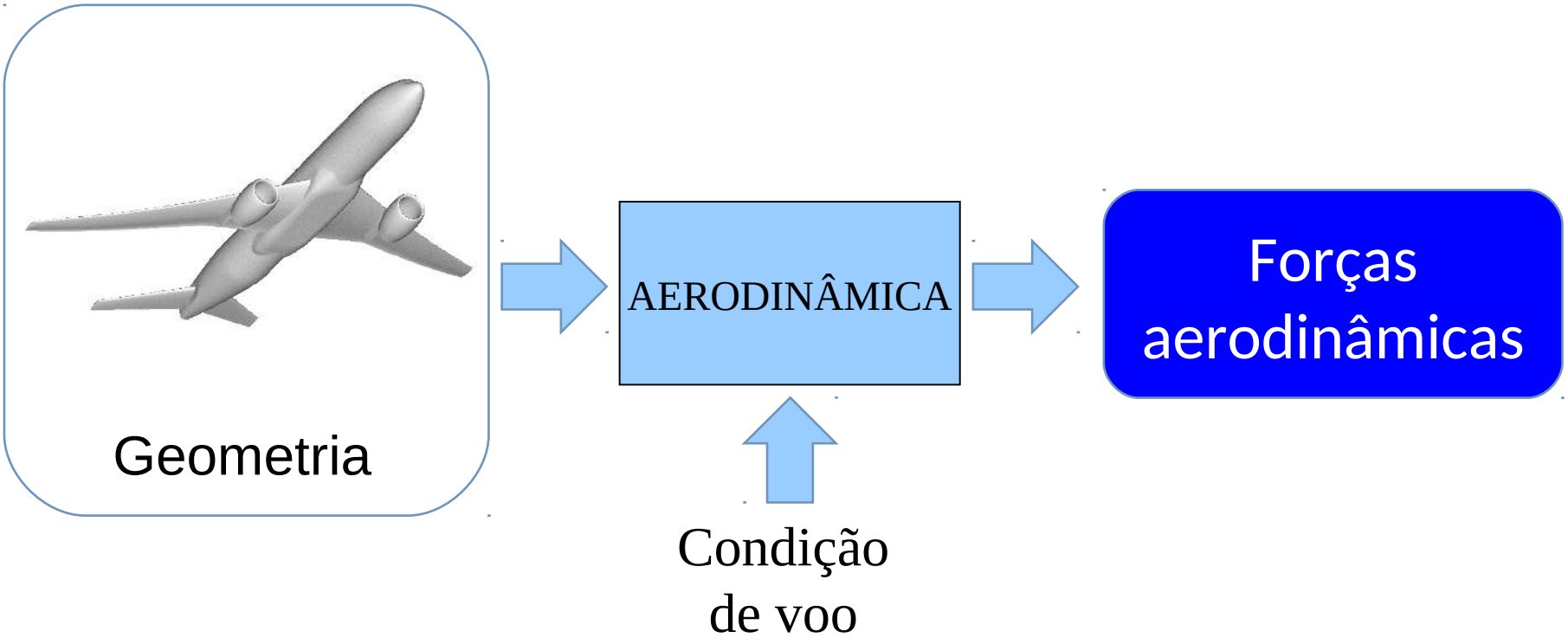
Instituto Tecnológico de Aeronáutica
Mestrado Profissional em Engenharia Aeronáutica

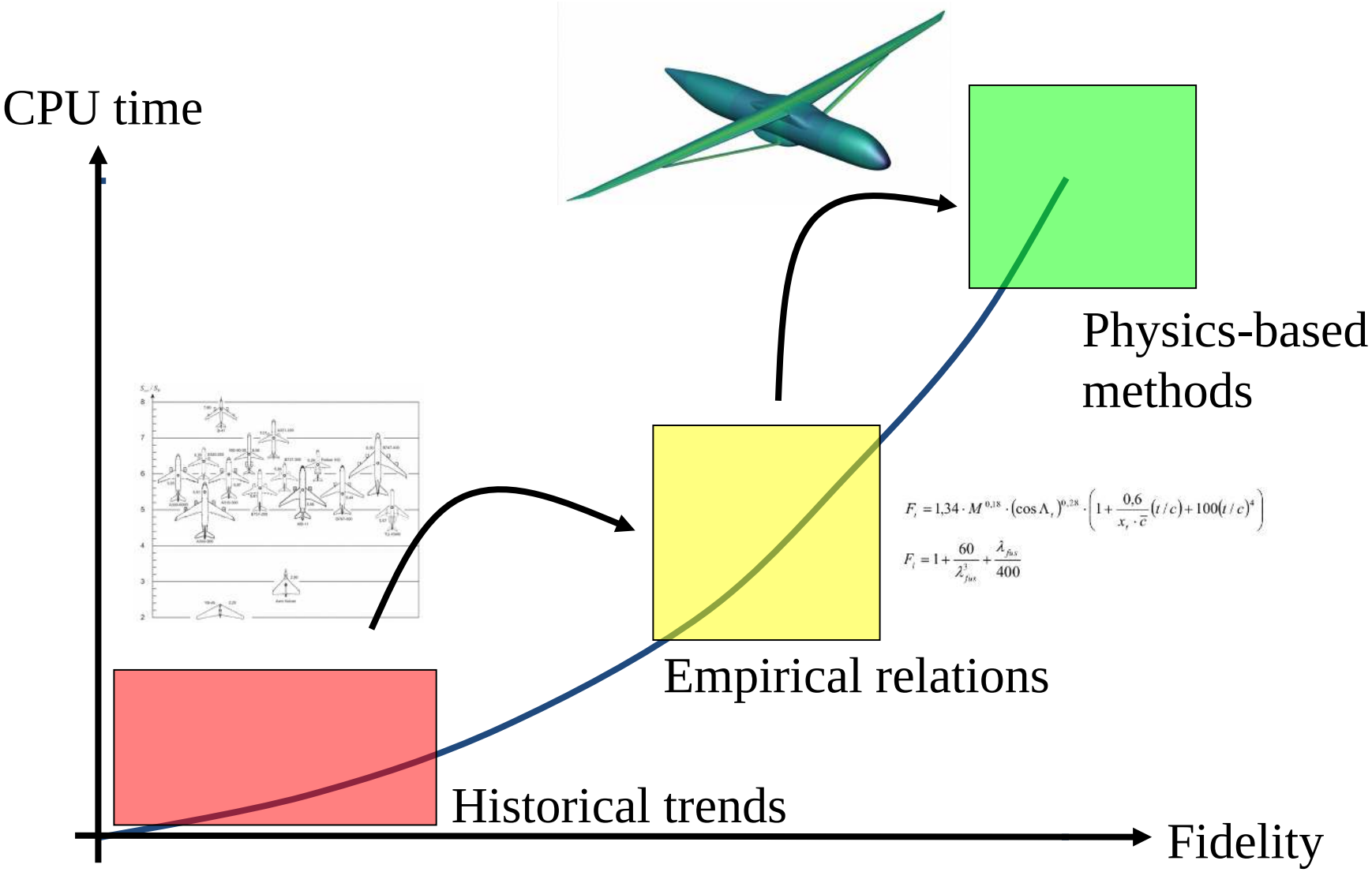
AP-701
Fundamentos do Projeto de Aeronaves

Aula 3 – Aerodinâmica

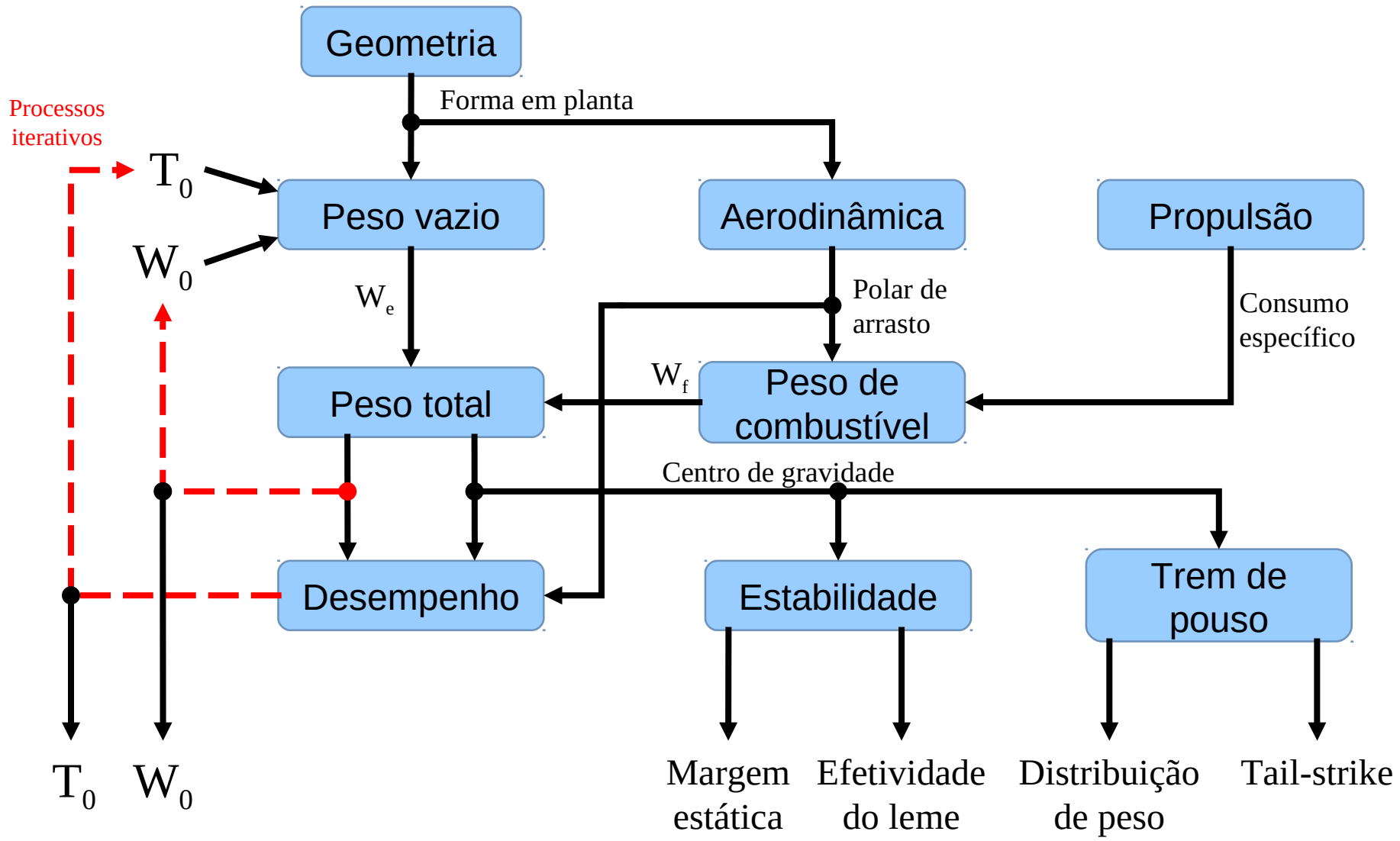
Cap. Ney Sêcco


Geometria
AERODINÂMICA
Forças aerodinâmicas
Condição de voo

How do we estimate aerodynamic characteristics?

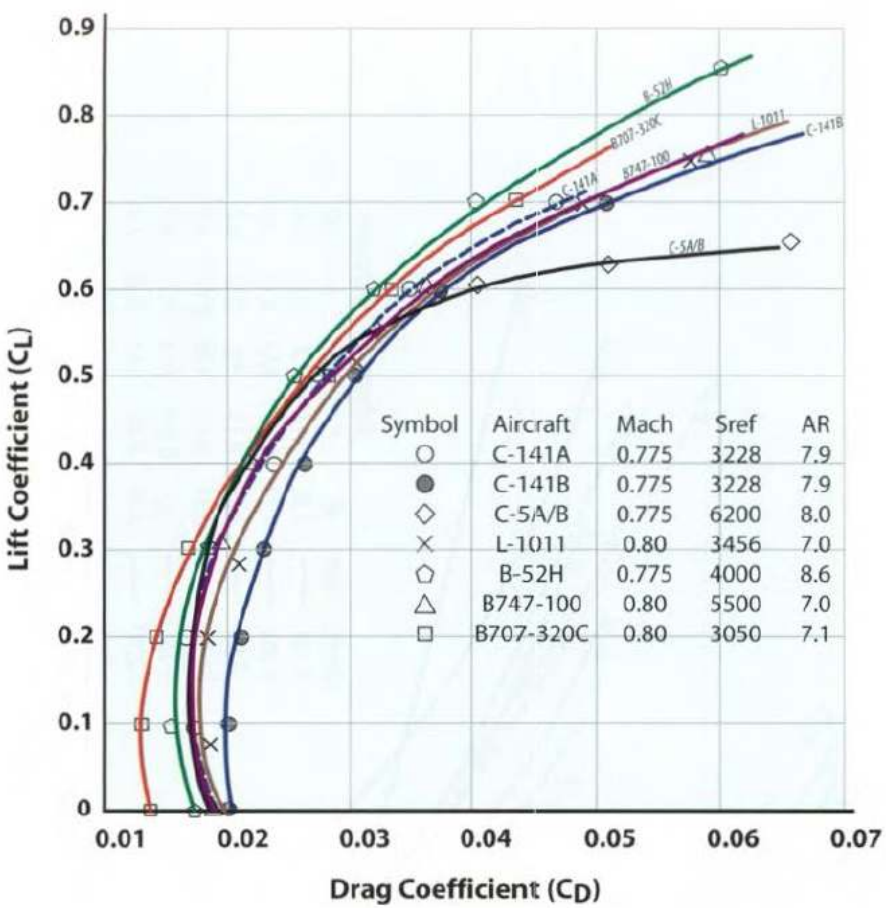


Fluxo de análise



Aerodynamics during conceptual sizing

- Conceptual sizing requires a drag polar.
- Drag polar represents the trade-off between lift and drag.
- Drag polar changes with Reynolds number, Mach number, and configuration (flaps, landing gear, etc…)



Projeto de superfícies aerodinâmicas

- Seleção de aerofólios
- Definição de forma em planta
- Dispositivos de hiper-sustentação
- Dispositivos de controle

Projeto de superfícies aerodinâmicas

- Seleção de aerofólios
- Definição de forma em planta
- Dispositivos de hiper-sustentação
- Dispositivos de controle

Tipos de aerofólios

Symmetrical airfoils

NACA 0012

Cambered airfoils

RG 14

High-lift airfoils

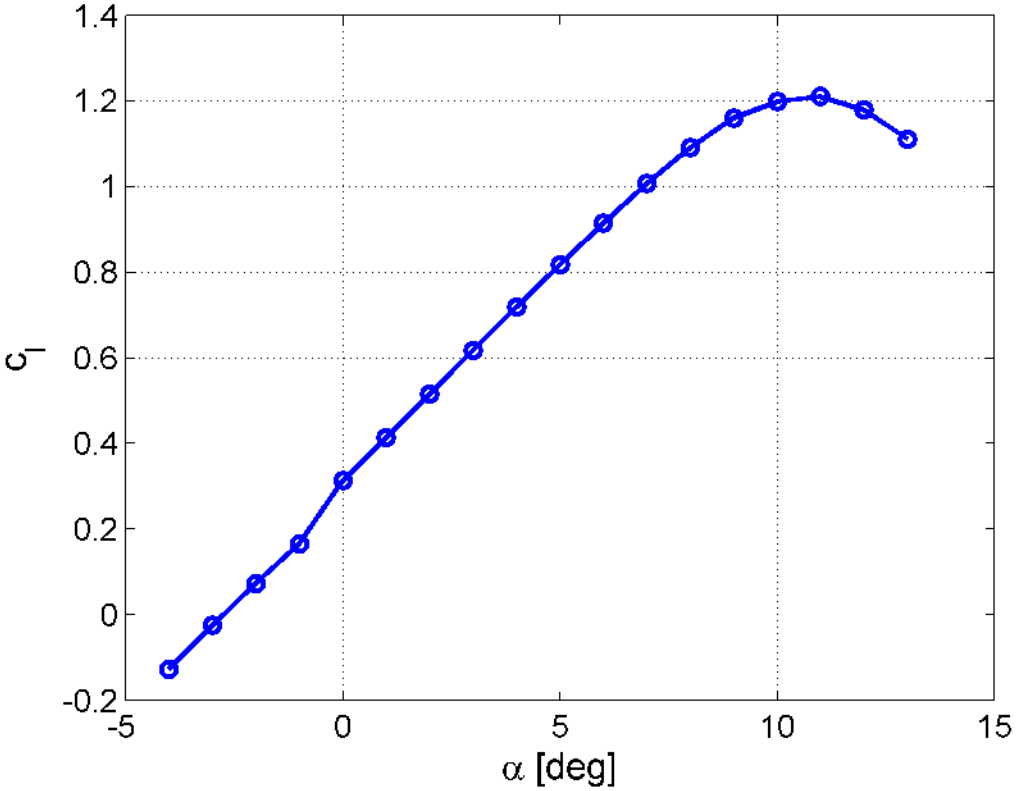
Selig 1223

Reflex airfoils

Eppler 325

Want more?: Google UIUC Airfoil Data Site

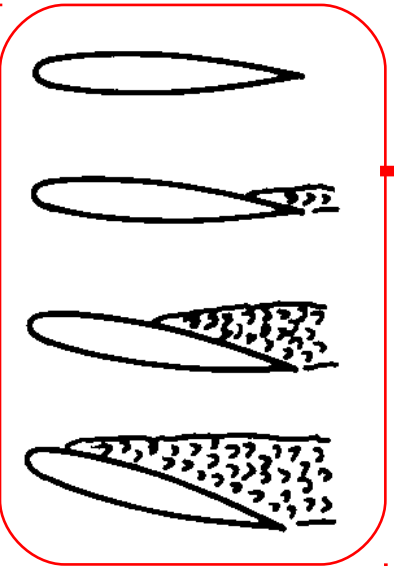
Curvas principais



MH32 airfoil
Re 4.4e5
XFOIL

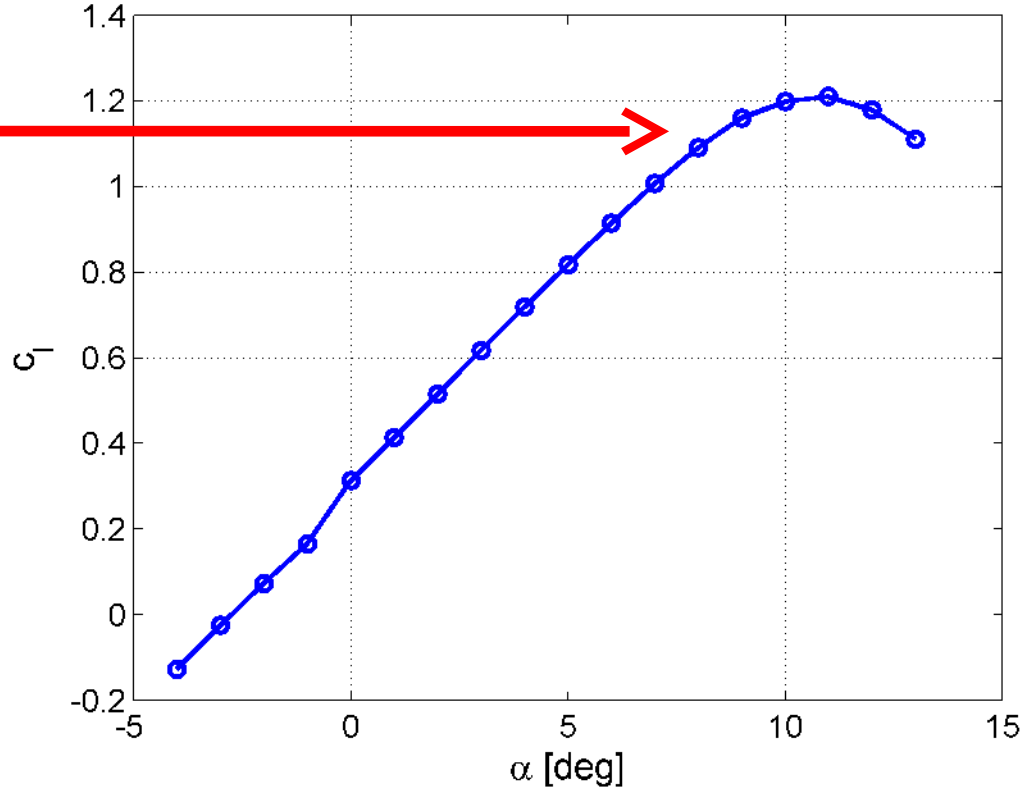
Curva de sustentação
CL vs α

Curvas principais



stall

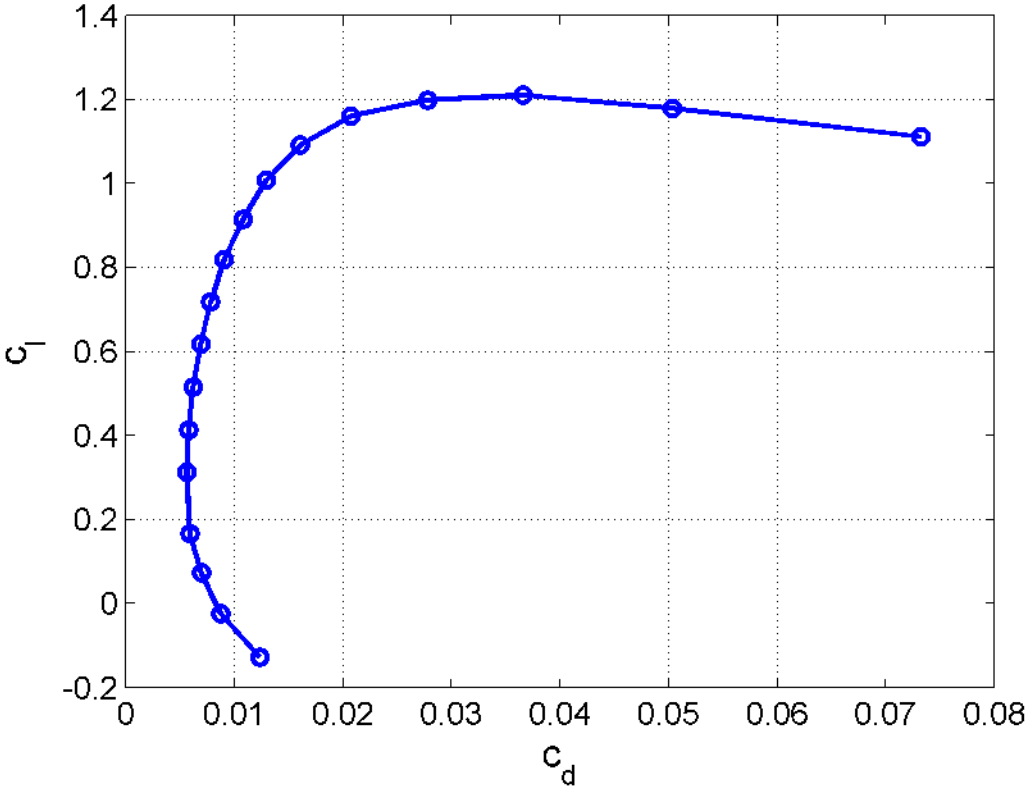
Raymer, 1992



MH32 airfoil
Re 4.4e5
XFOIL

Curva de sustentação
CL vs α

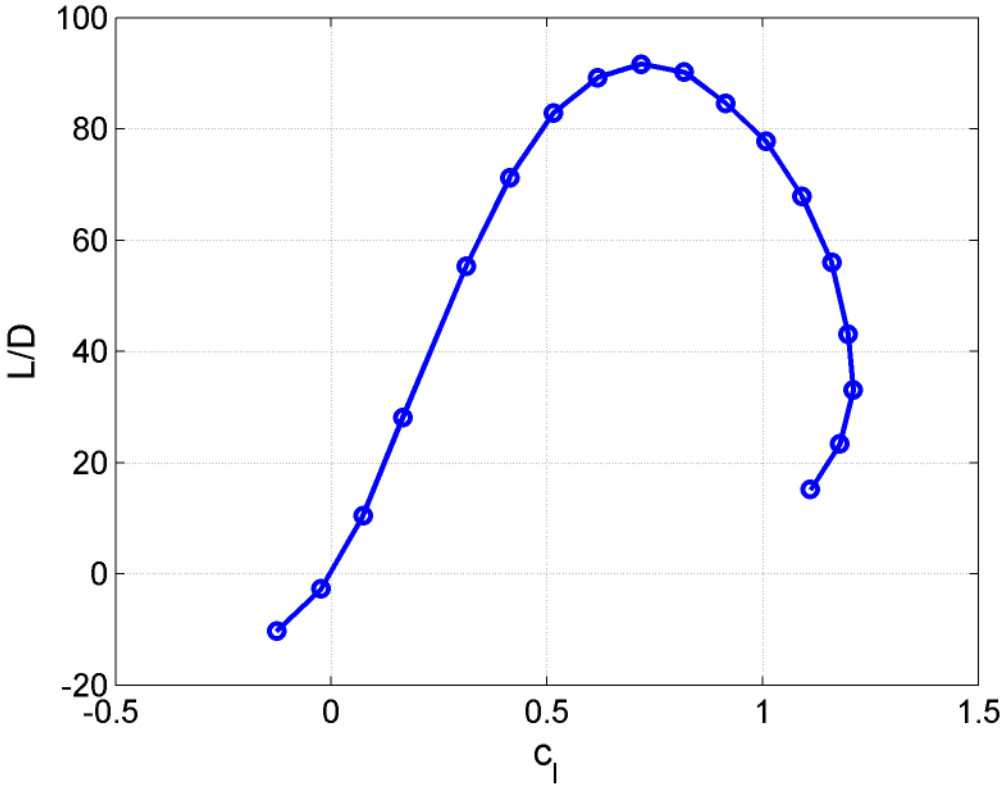
Curvas principais



MH32 airfoil
Re 4.4e5
XFOIL

Polar de arrasto
CL vs CD

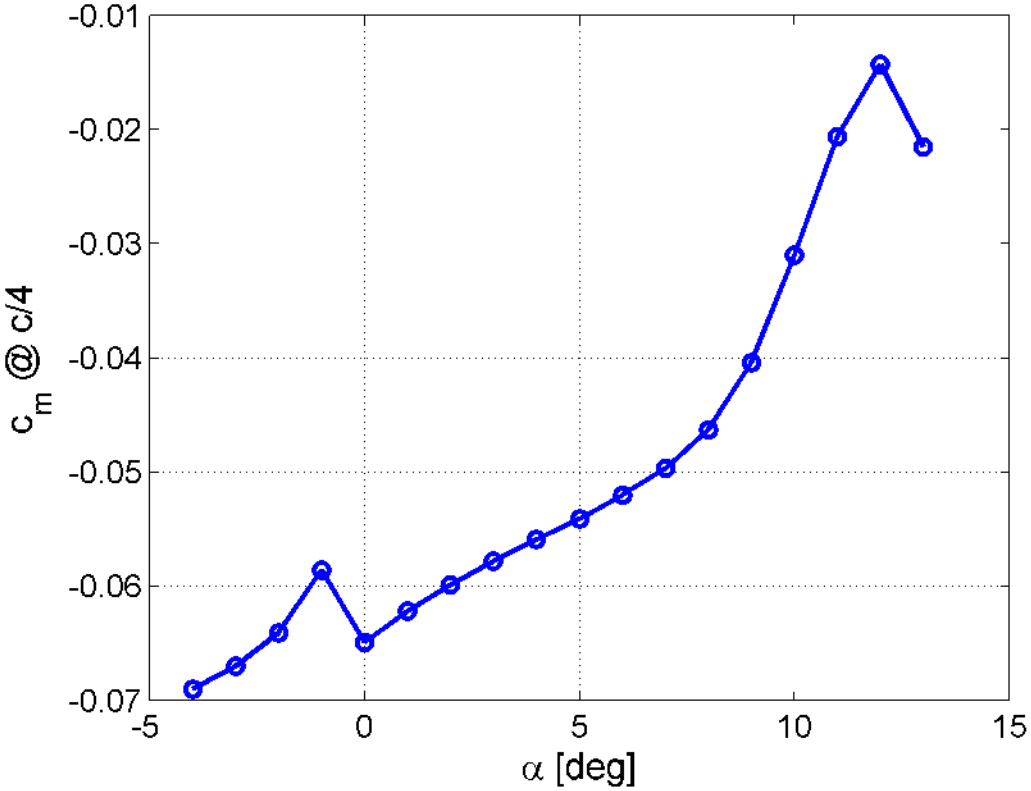
Curvas principais



MH32 airfoil
Re 4.4e5
XFOIL

Eficiência aerodinâmica
CM vs α

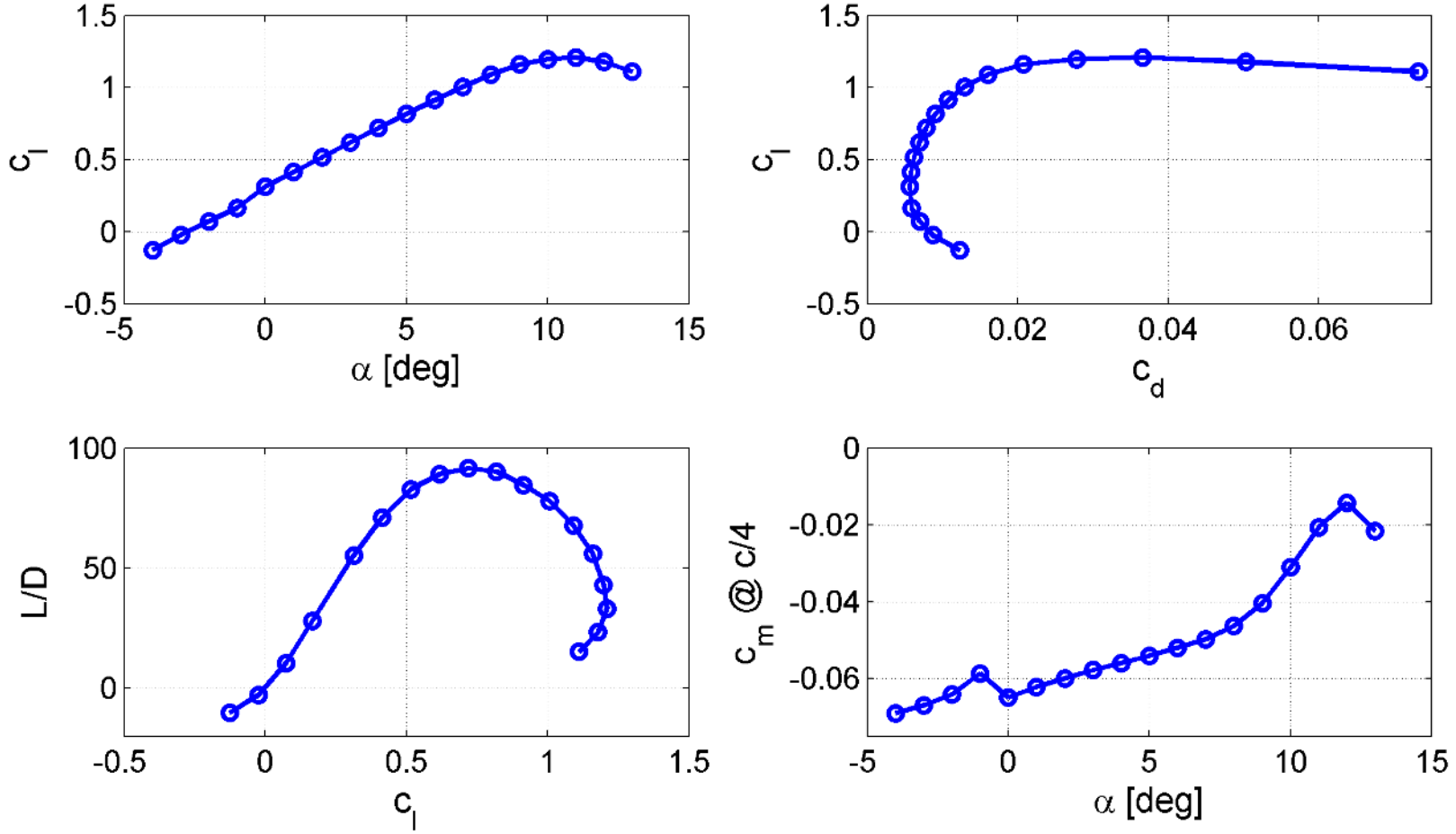
Curvas principais



MH32 airfoil
Re 4.4e5
XFOIL

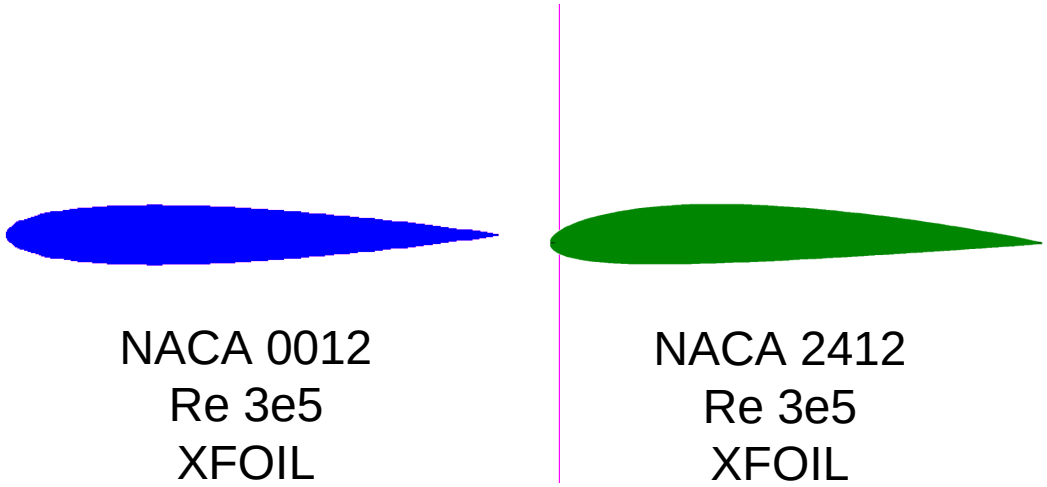
Curva de momento
CM vs α

Curvas principais

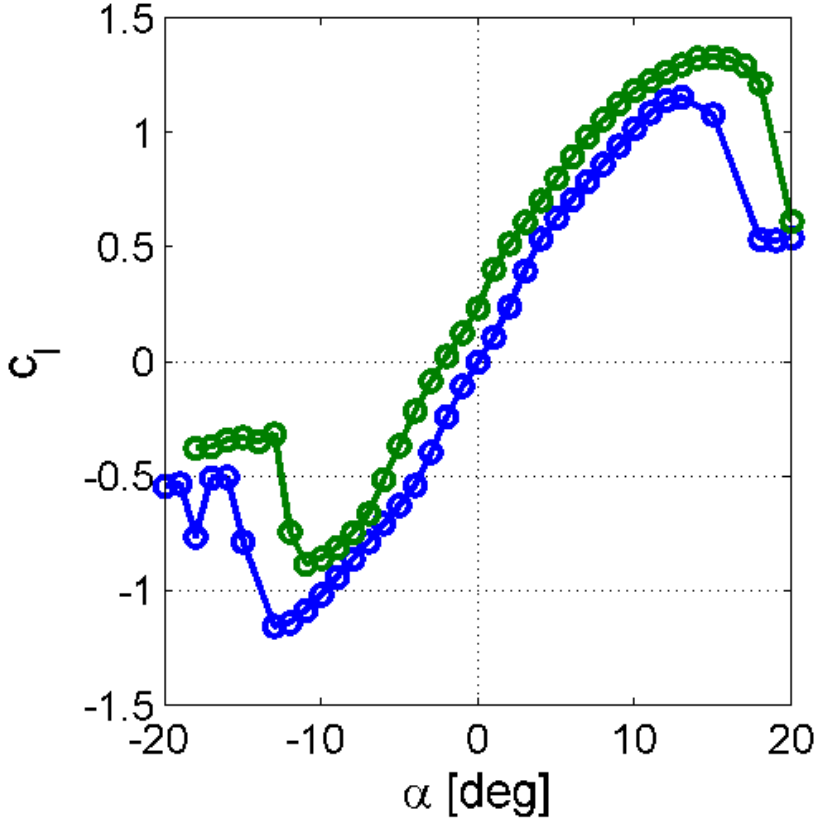


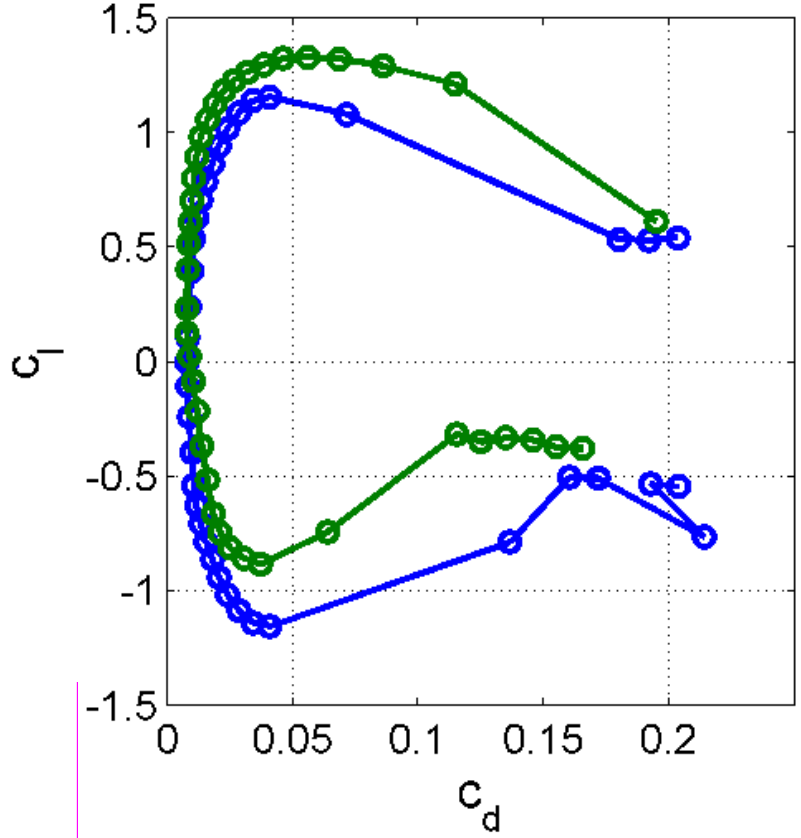
MH32 airfoil
Re 4.4e5
XFOIL

Arqueamento



Arqueamento



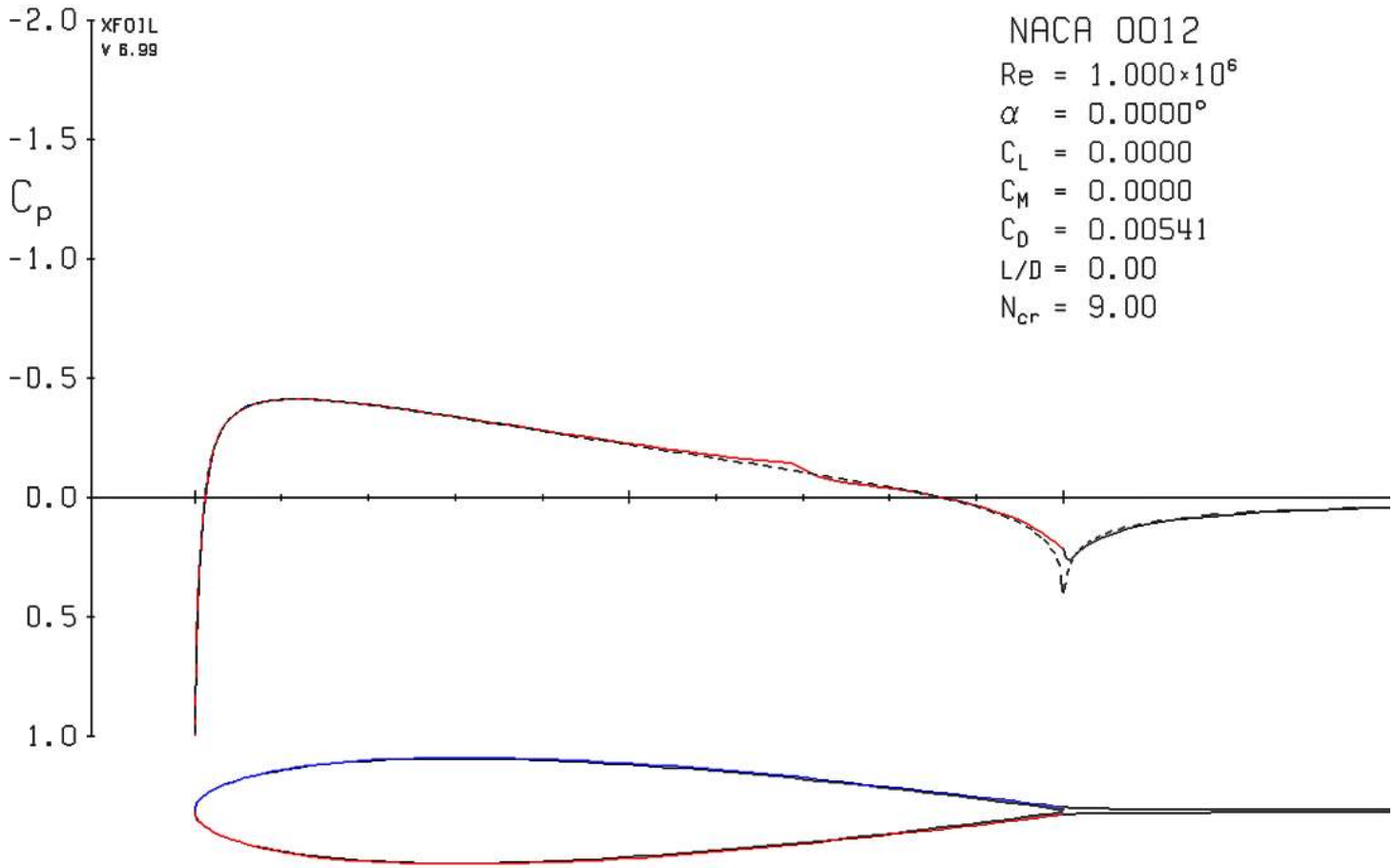


NACA 0012
Re 3e5
XFOIL

NACA 2412
Re 3e5
XFOIL

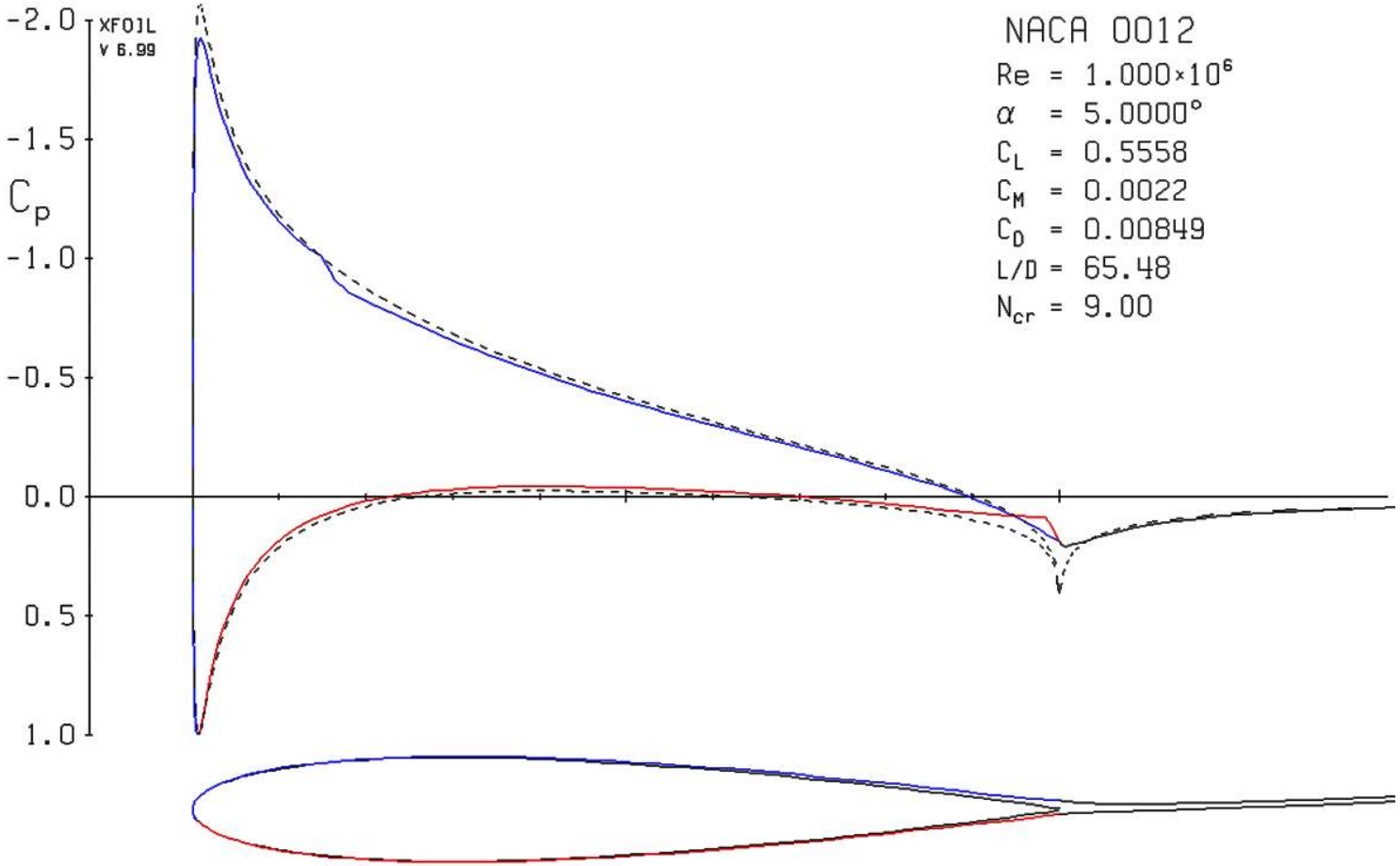
Curvas de pressão demonstram características dos aerofólios

- Aerofólio simétrico, alpha = 0 grau



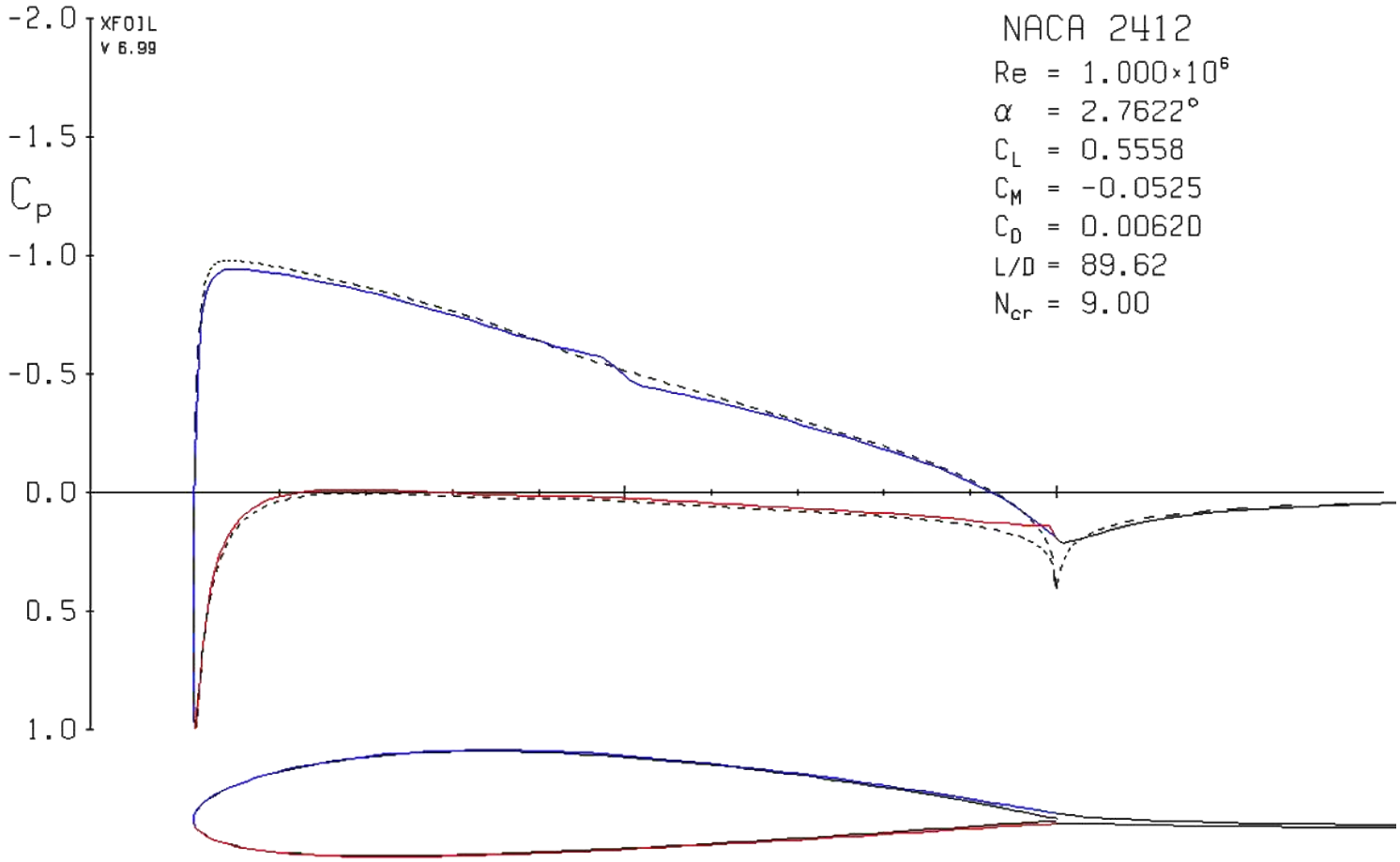
Curvas de pressão demonstram características dos aerofólios

- Aerofólio simétrico, alpha = 5 graus



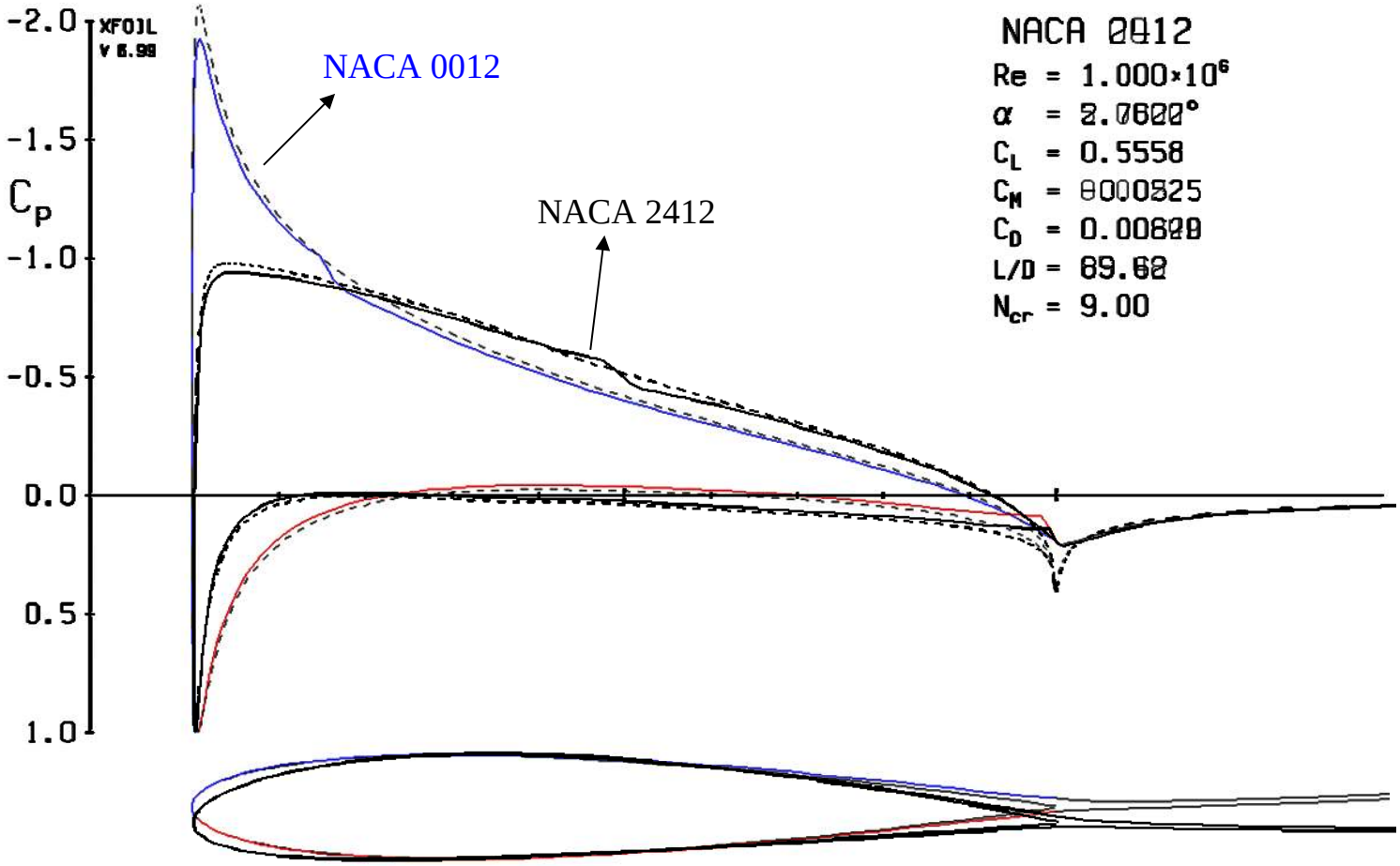
Curvas de pressão demonstram características dos aerofólios

- Aerofólio arqueado, alpha = 2,76 graus

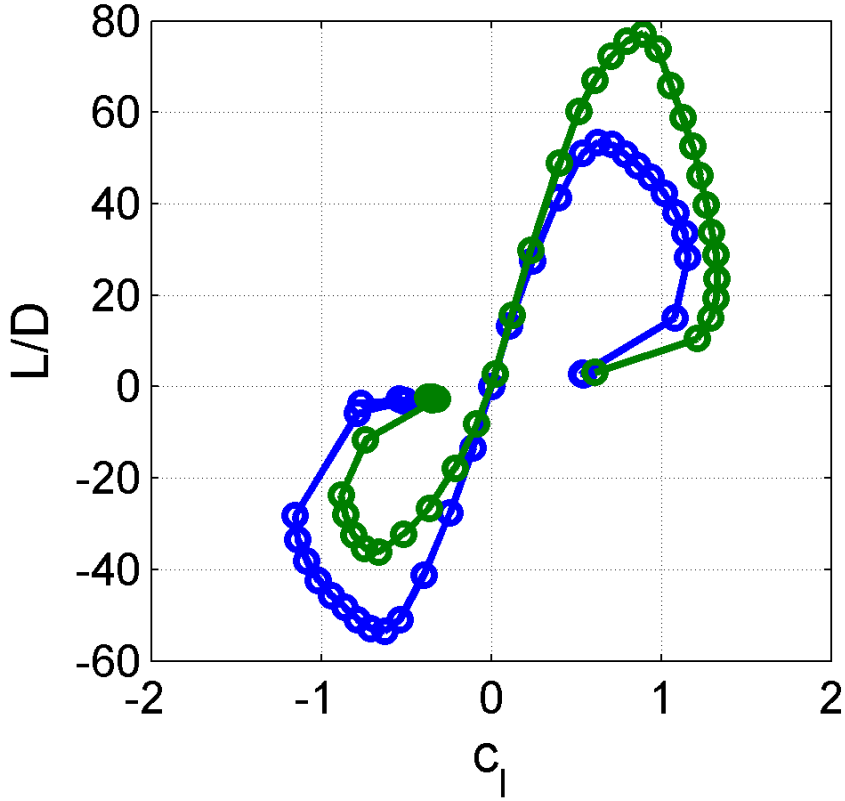


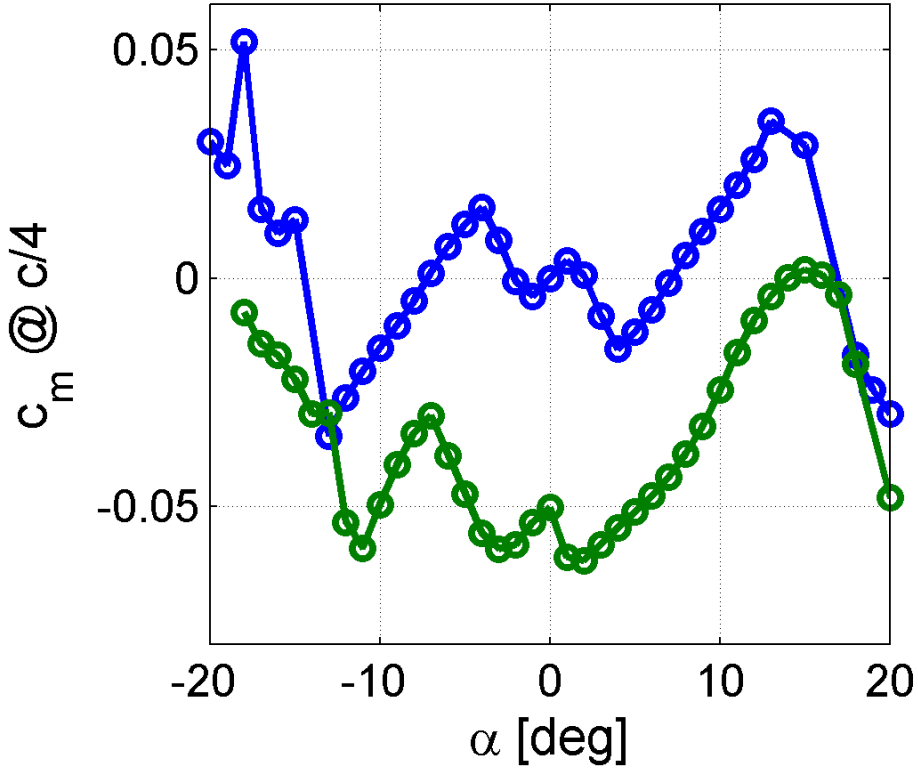
Curvas de pressão demonstram características dos aerofólios

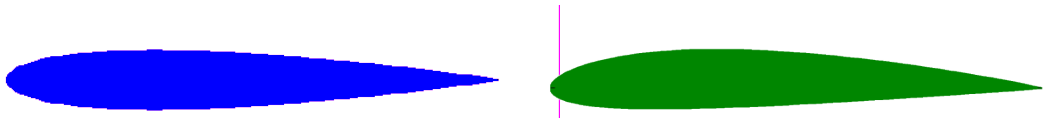
- Comparação de aerofólios



Arqueamento



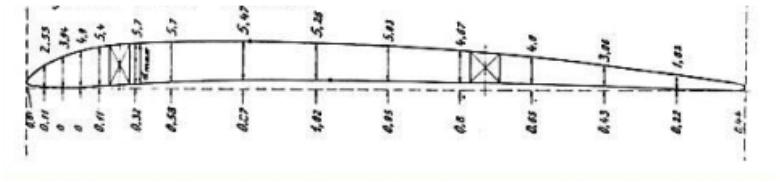




NACA 0012
Re 3e5
XFOIL

NACA 2412
Re 3e5
XFOIL

Perfis mais espessos foram introduzidos na 1ª Guerra Mundial



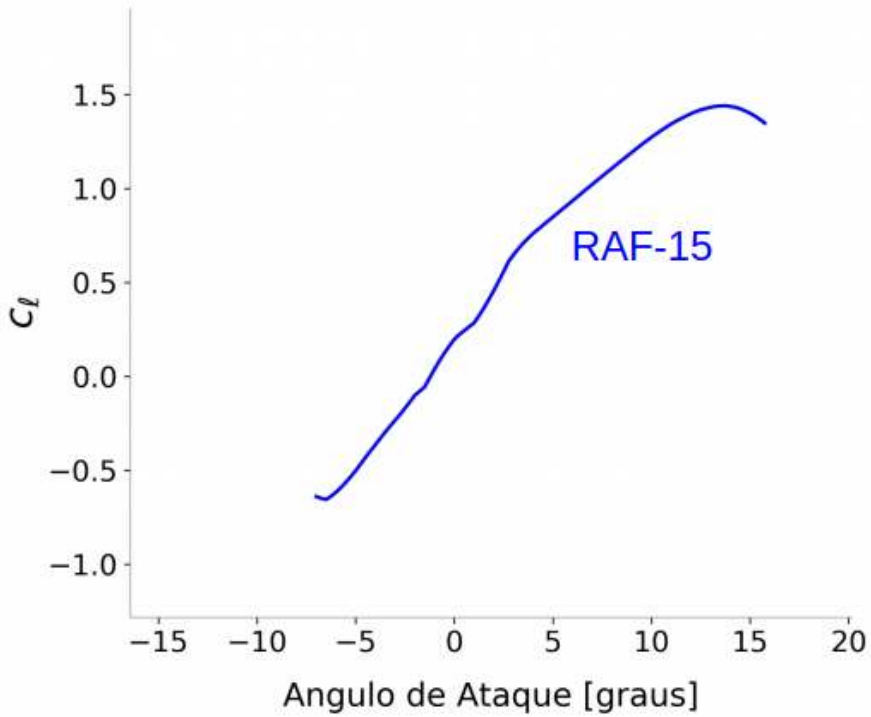
RAF-15
6,5% de espessura

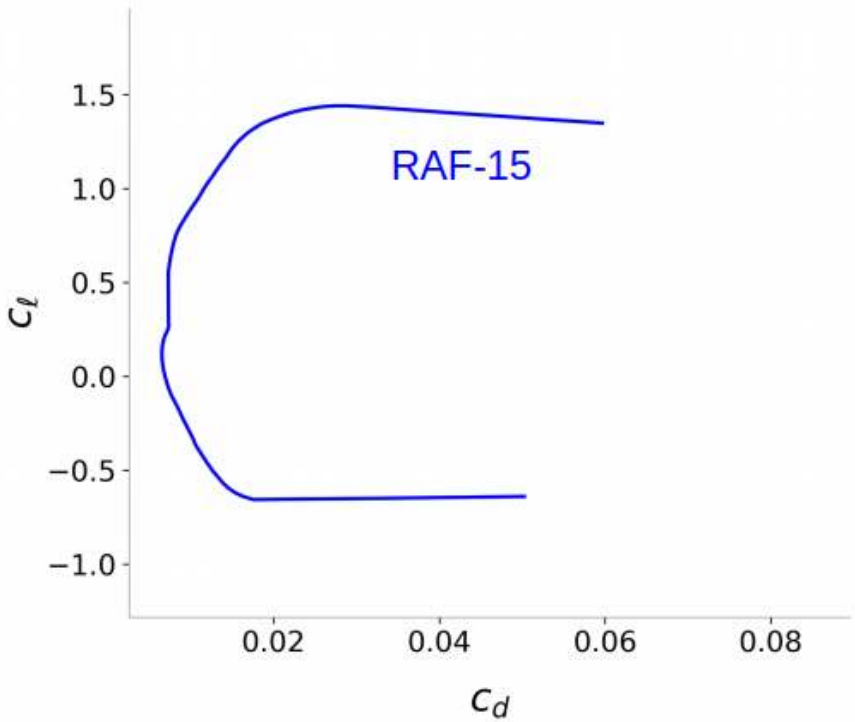
Sopwith Camel - 1917

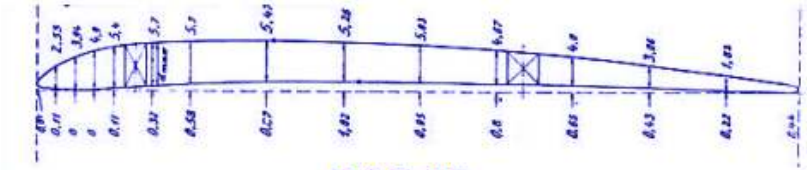
Gottingen 298
12,8% de espessura

Fokker Dr.I - 1917

Perfis espessos têm melhor eficiência aerodinâmica em alto C_L



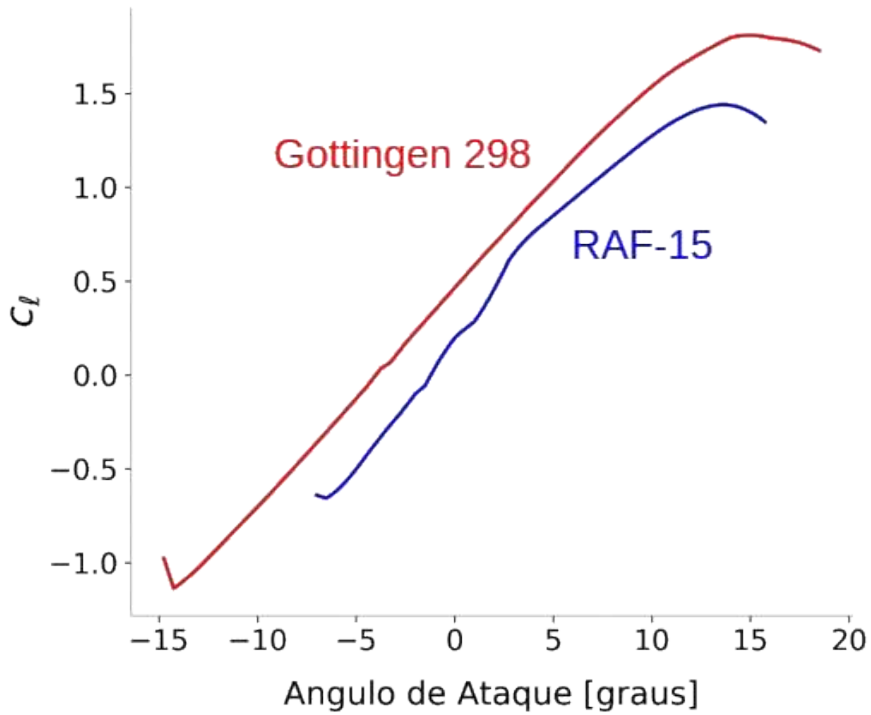


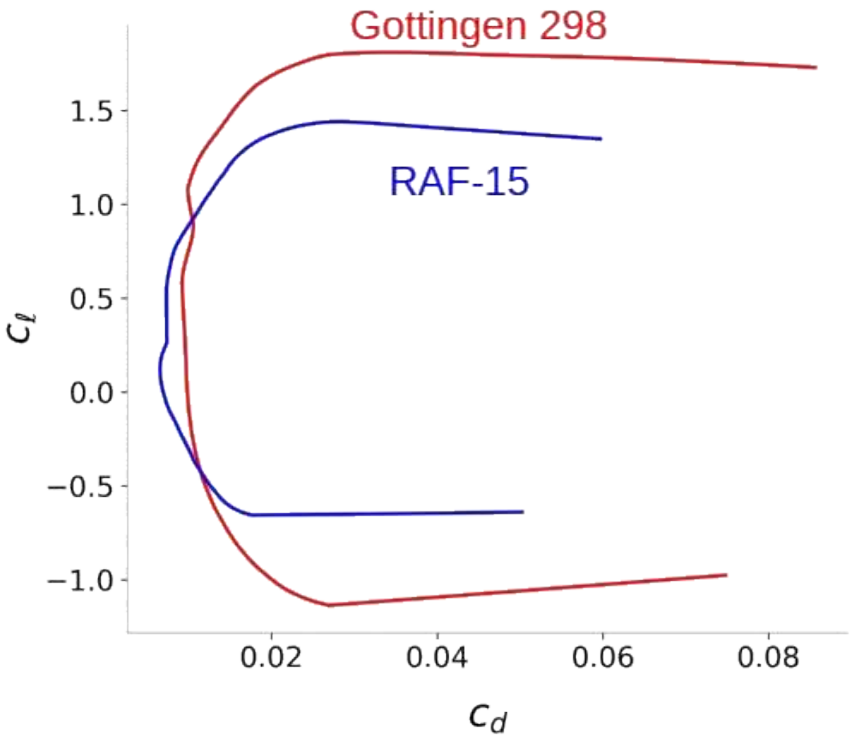


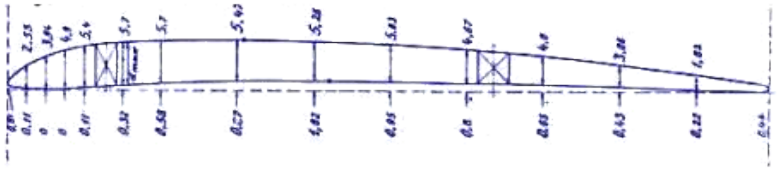
RAF-15

t/c = 6,5%

Perfis espessos têm melhor eficiência aerodinâmica em alto C_L







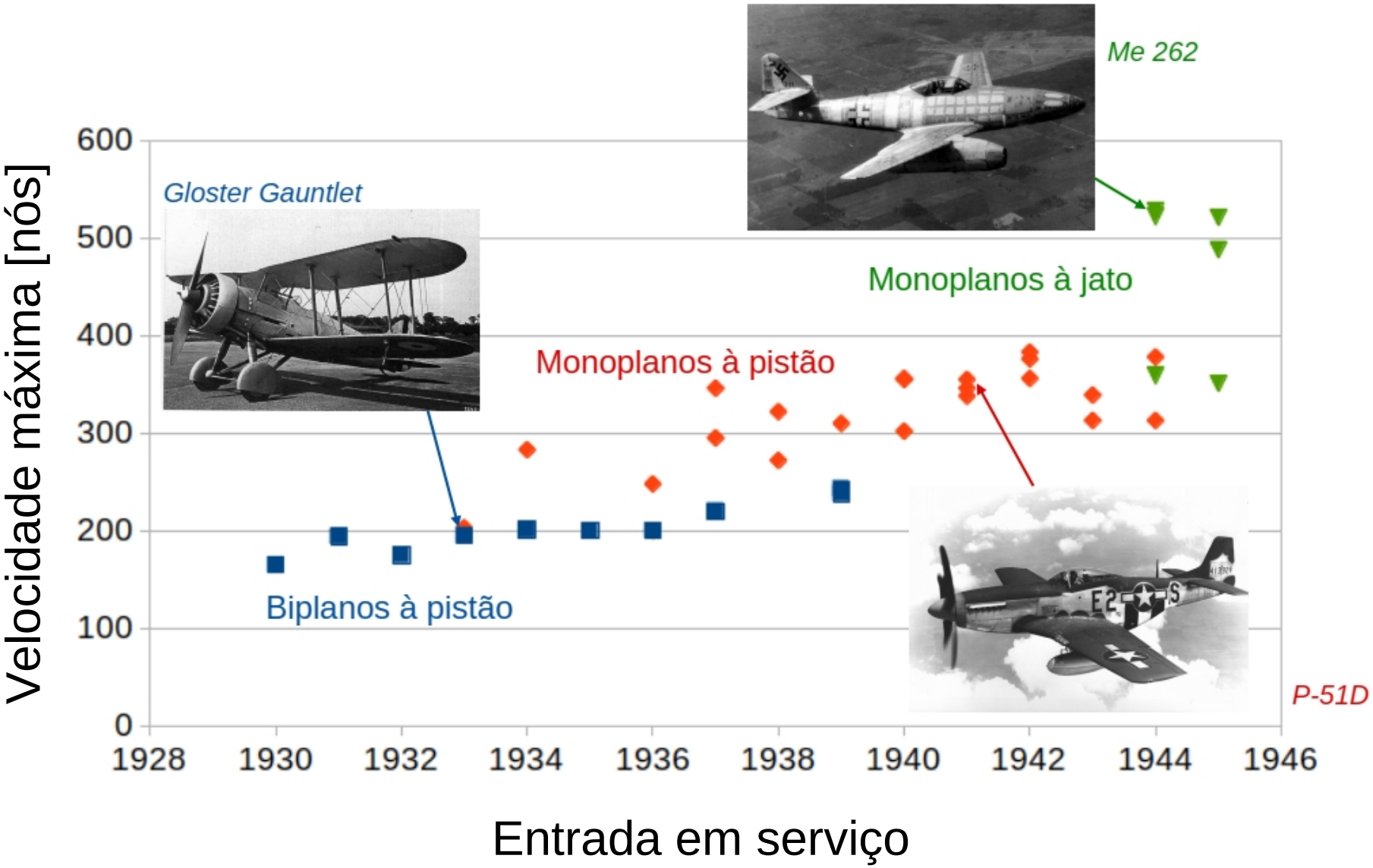
RAF-15

t/c = 6,5%

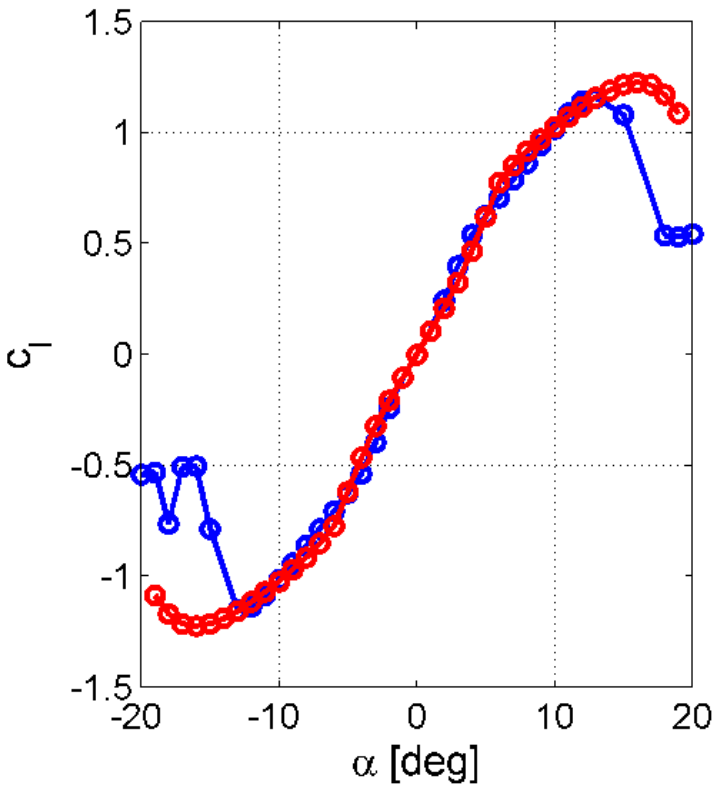
Gottingen 298

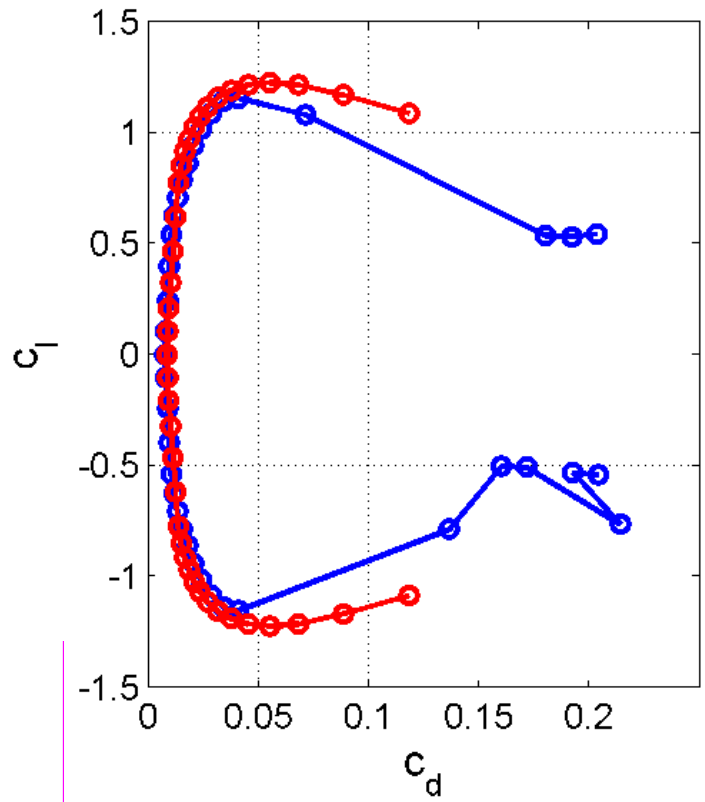
t/c = 12,8%

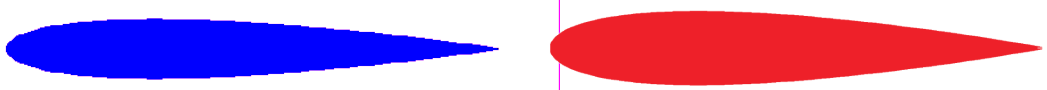
Novas tecnologias aerodinâmicas e propulsivas foram introduzidas na 2ª Guerra Mundial



Espessura



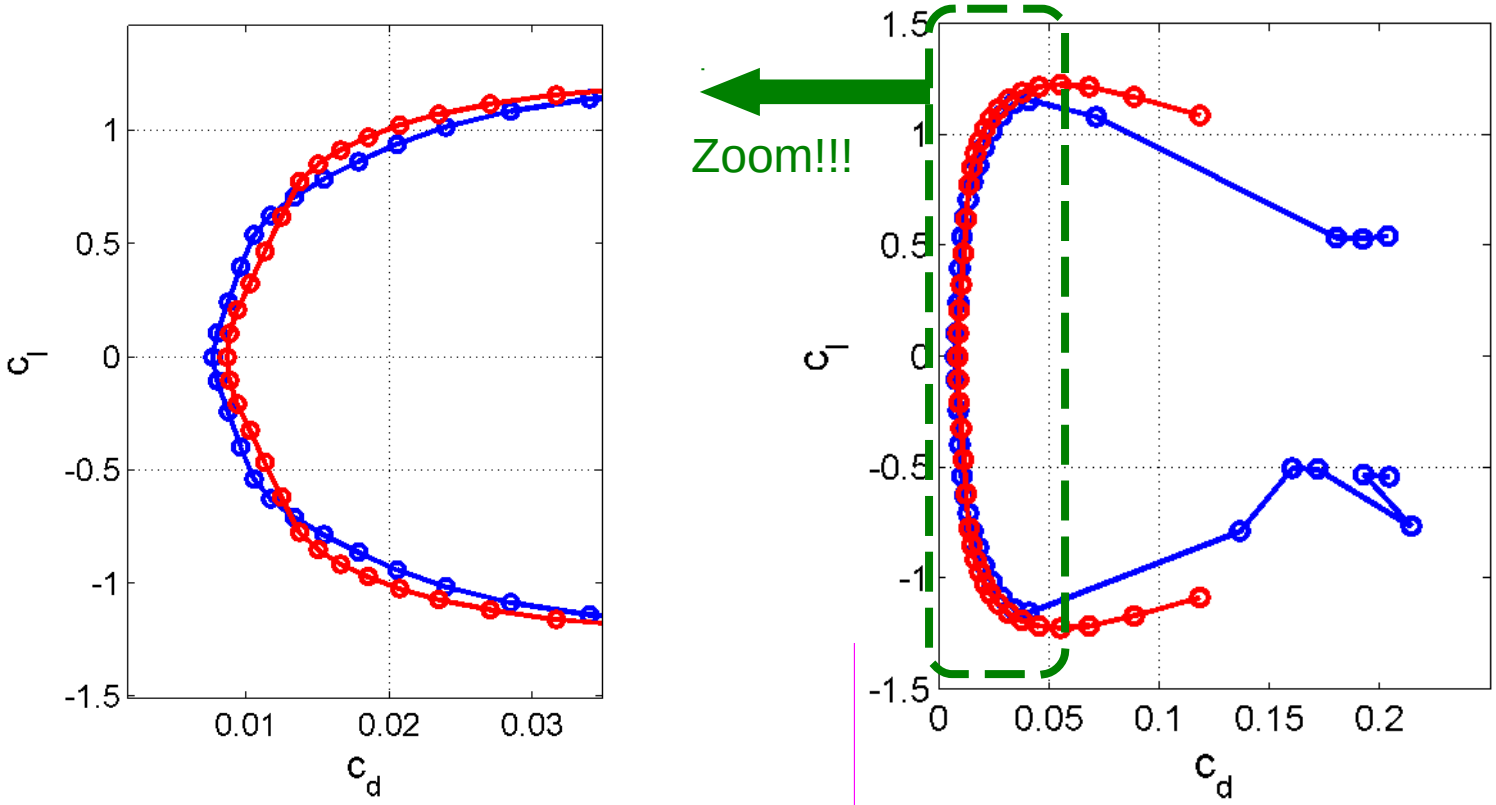


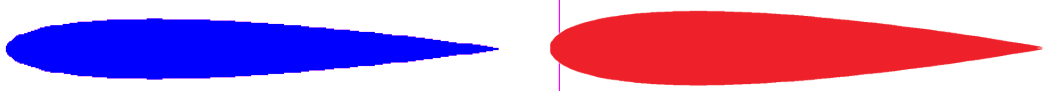


NACA 0012
Re 3e5
XFOIL

NACA 0015
Re 3e5
XFOIL

Espessura





NACA 0012
Re 3e5
XFOIL

NACA 0015
Re 3e5
XFOIL

Qual desses aerofólios são usados em aeronaves comerciais transônicas?

Symmetrical airfoils

NACA 0012

Cambered airfoils

RG 14

High-lift airfoils

Selig 1223

Reflex airfoils

Eppler 325

Want more?: Google UIUC Airfoil Data Site

Aerofólios supercríticos atrasam o surgimento de ondas de choque

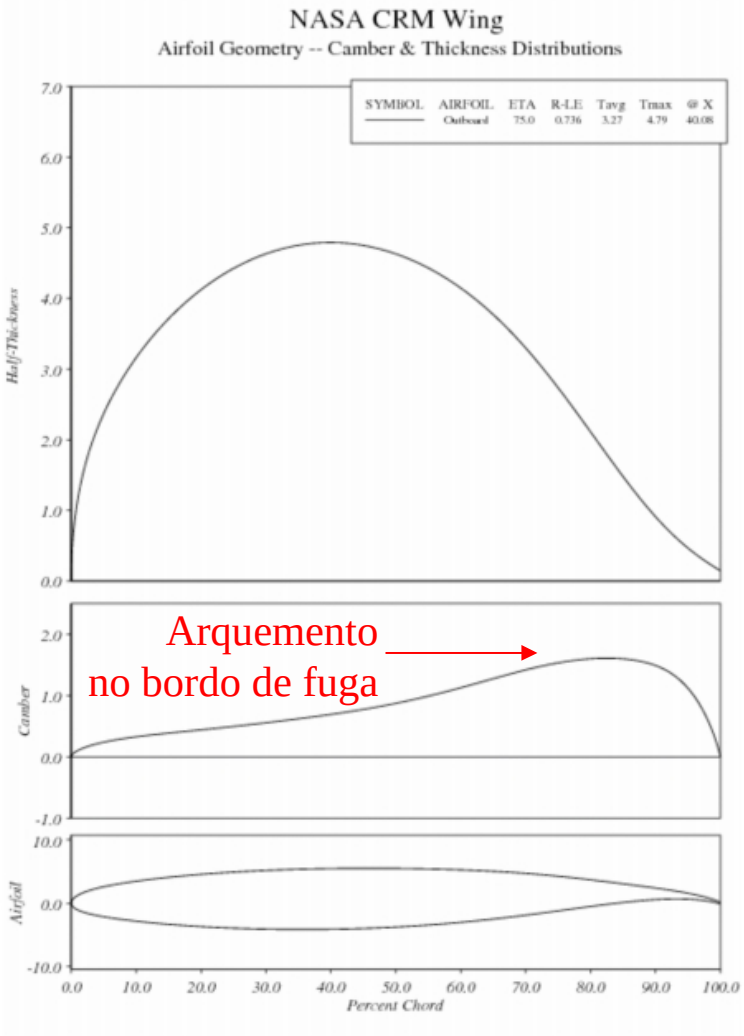
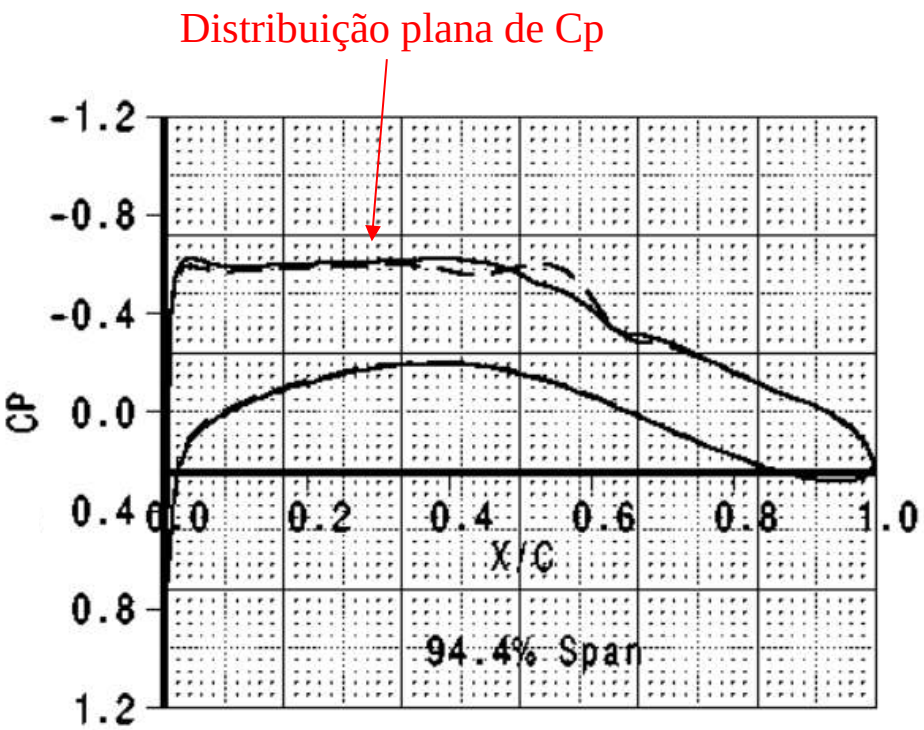


Figure 8: Airfoil Characteristics at an Outboard Station of the CRM Wing.

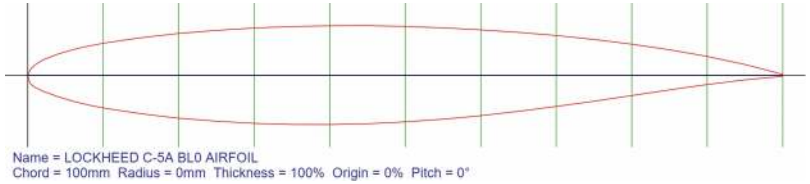


Vassberg, et. al., 2008

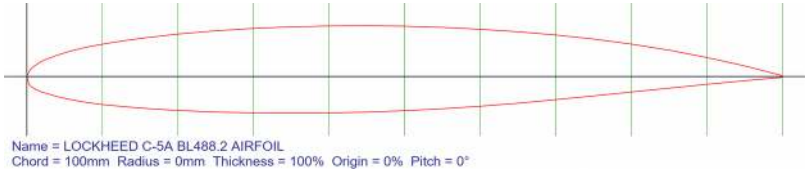
Torção aerodinâmica

C-5 Galaxy

0% semi-span
t/c = 13,1%
camber = 0,7%

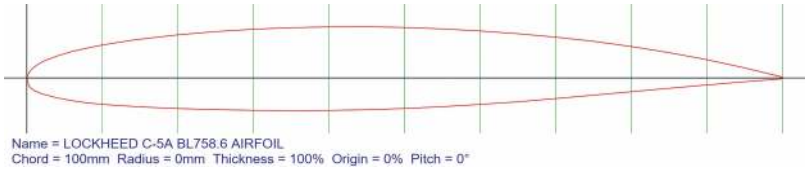


36% semi-span
t/c = 11,5%
camber = 1,2%

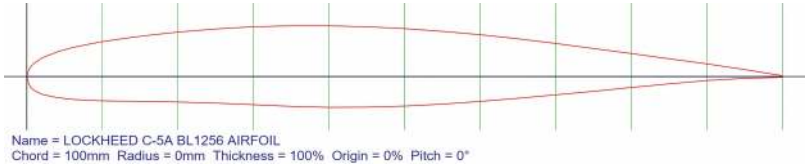


43% semi-span
t/c = 11,1%
camber = 1,4%

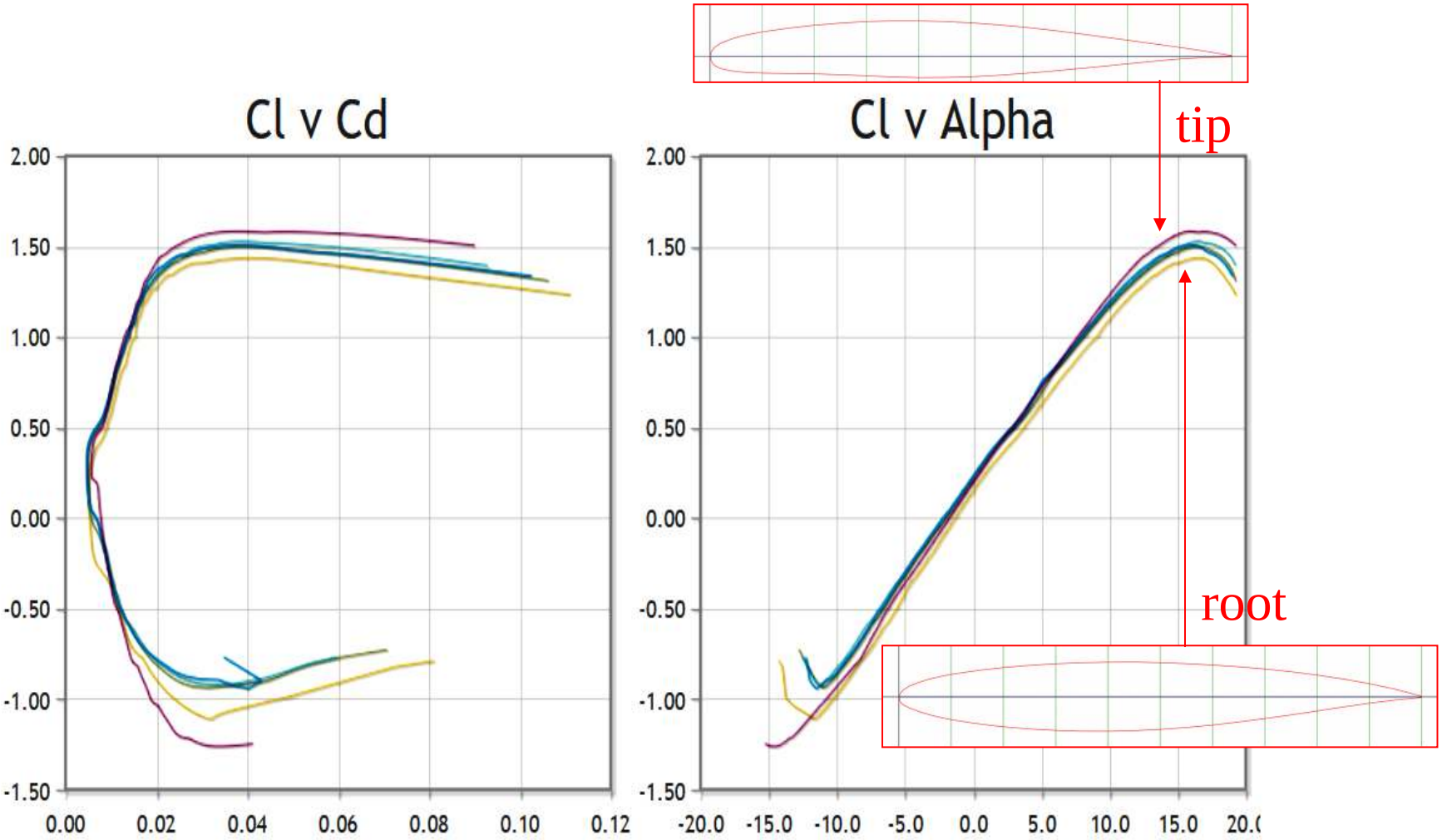
57% semi-span
t/c = 11,1%
camber = 1,4%



94% semi-span
t/c = 10,8%
camber = 1,4%



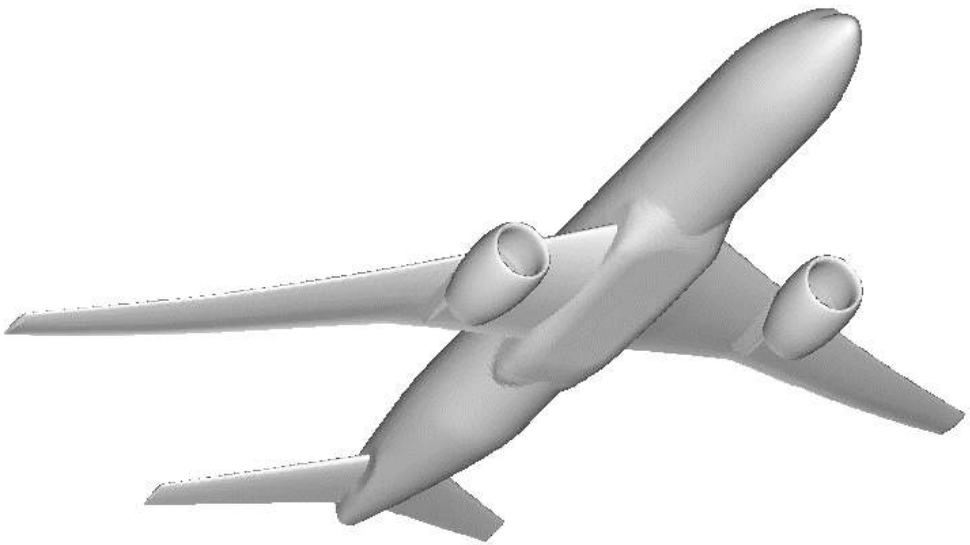
Torção aerodinâmica

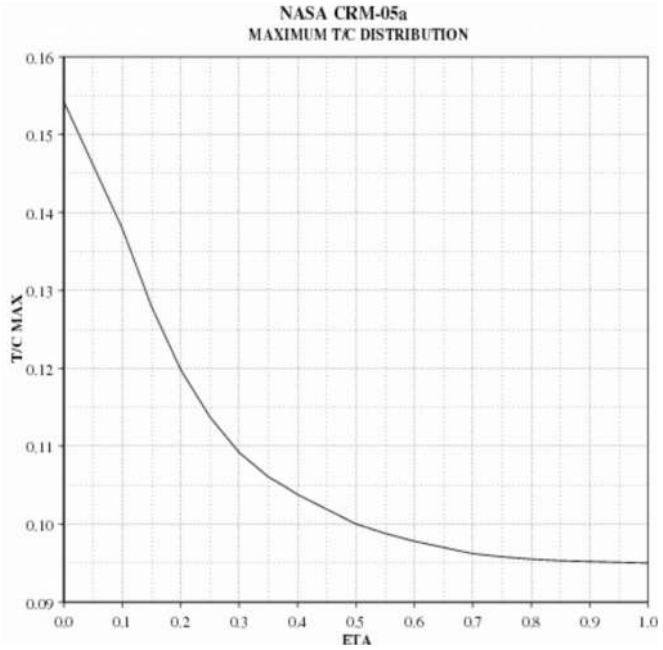


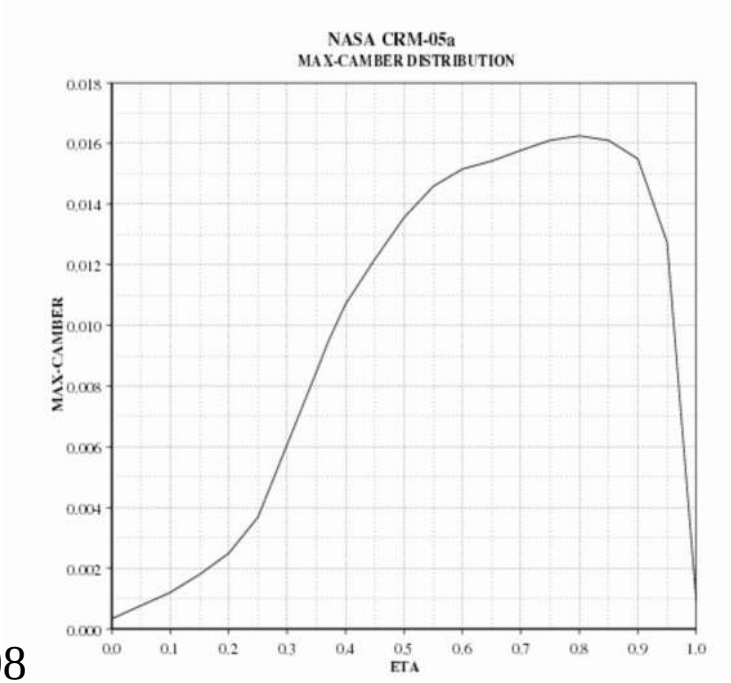
Re = 1e6

Torção aerodinâmica

NASA Common Research Model (CRM)







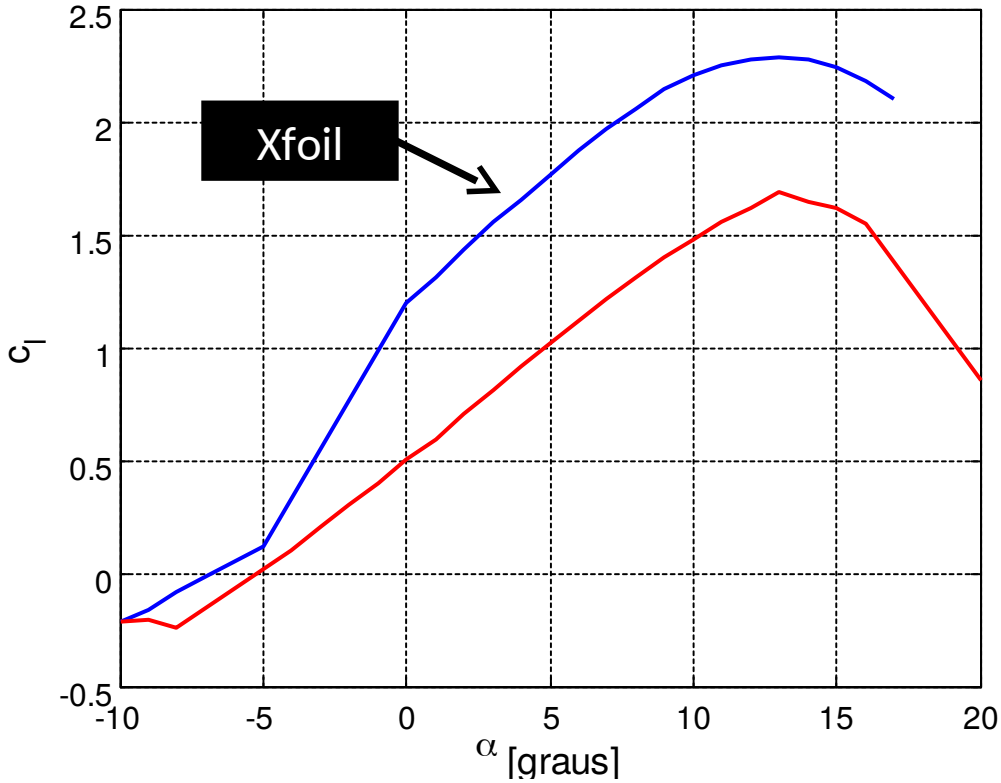
- Geometria baseada no B777
- Usado para verificação de códigos de CFD

Vassberg, et. al., 2008

Manufacturing

Olafesky 02

Selig 1223

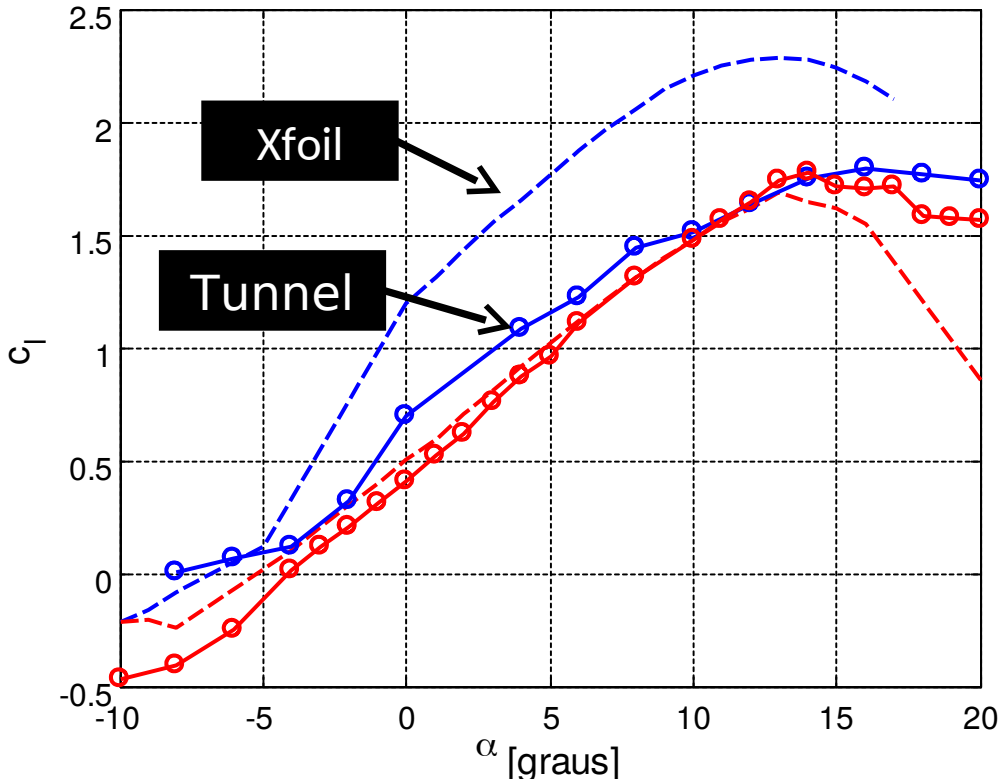


$Re=2\cdot10^5$

Manufacturing

Olafesky 02

Selig 1223



$Re=2\cdot10^5$

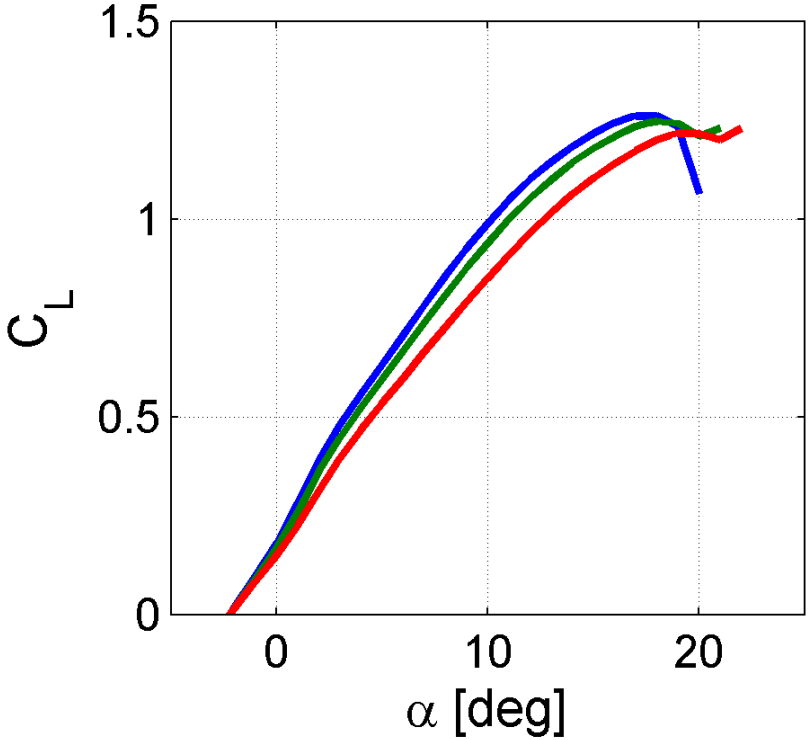
Tendências gerais

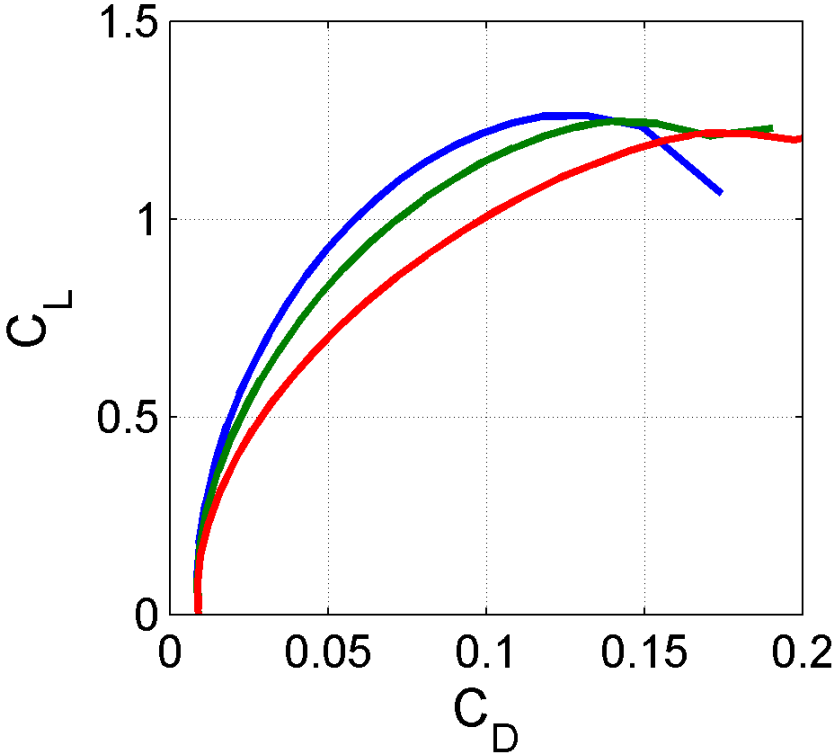
- Maior Arqueamento...
  - Maior $c_{\ell max}$
  - Maior $c_{\ell min}$
  - Melhor eficiência aerodinâmica para altos c_ℓ
  - Maior momento picador
- Maior Espessura...
  - Maior $c_{\ell max}$
  - Maior arrasto para baixos c_ℓ
  - Maior espaço para estruturas, sistemas e combustível
  - Maior arrasto de onda
- Aerofólios Supercríticos...
  - Menor arrasto de onda
  - Maior momento picador

Projeto de superfícies aerodinâmicas

- Seleção de aerofólios
- Definição de forma em planta
- Dispositivos de hiper-sustentação
- Dispositivos de controle

Alongamento





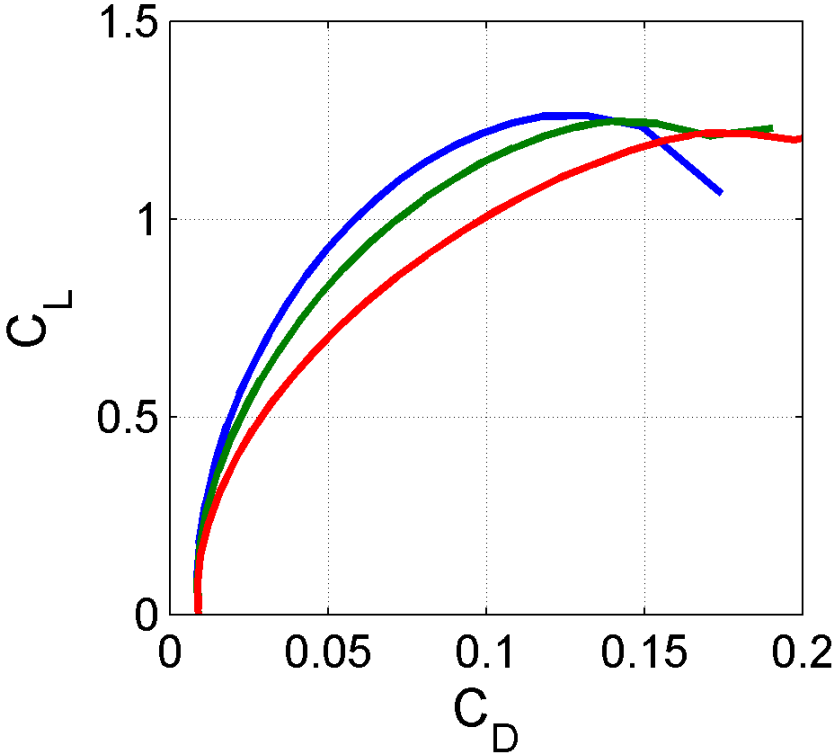
NACA 2412 wing
Re 3e5; AR=4
Non-linear LLT

NACA 2412 wing
Re 3e5; AR=6
Non-linear LLT

NACA 2412 wing
Re 3e5; AR=8
Non-linear LLT

Alongamento

$$C_{Dind} = K \cdot C_L^2$$



NACA 2412 wing
Re 3e5; AR=4
Non-linear LLT

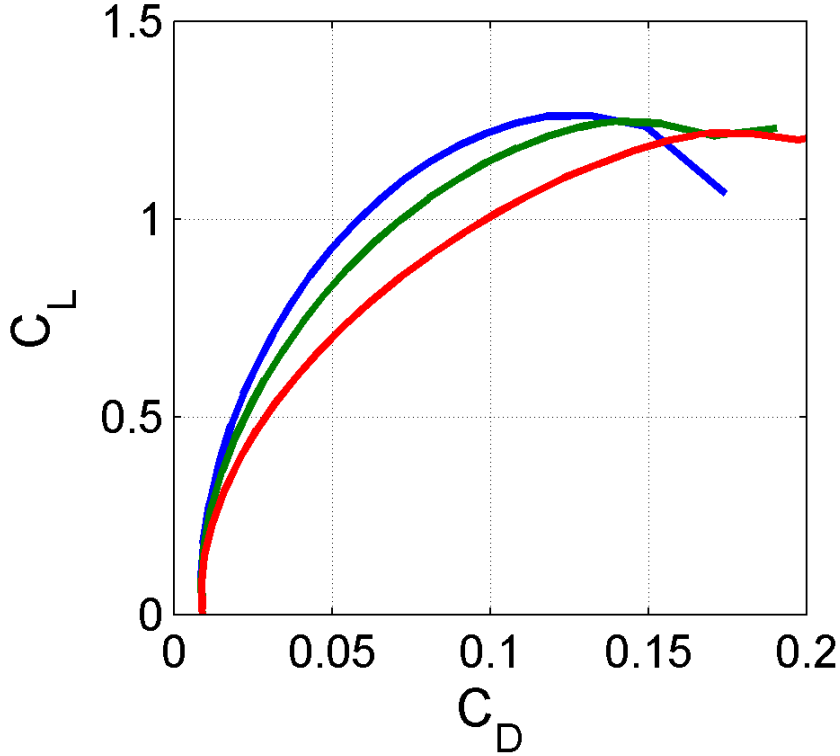
NACA 2412 wing
Re 3e5; AR=6
Non-linear LLT

NACA 2412 wing
Re 3e5; AR=8
Non-linear LLT

Alongamento

$$C_{Dind} = K \cdot C_L^2$$

$$C_{Dind} = \frac{1}{\pi \cdot AR \cdot e} C_L^2$$



NACA 2412 wing
Re 3e5; AR=4
Non-linear LLT

NACA 2412 wing
Re 3e5; AR=6
Non-linear LLT

NACA 2412 wing
Re 3e5; AR=8
Non-linear LLT

Examples of aspect ratios

airliners.net

airliners.net

Beechcraft Bonanza

AR: 6.2

ASK-21

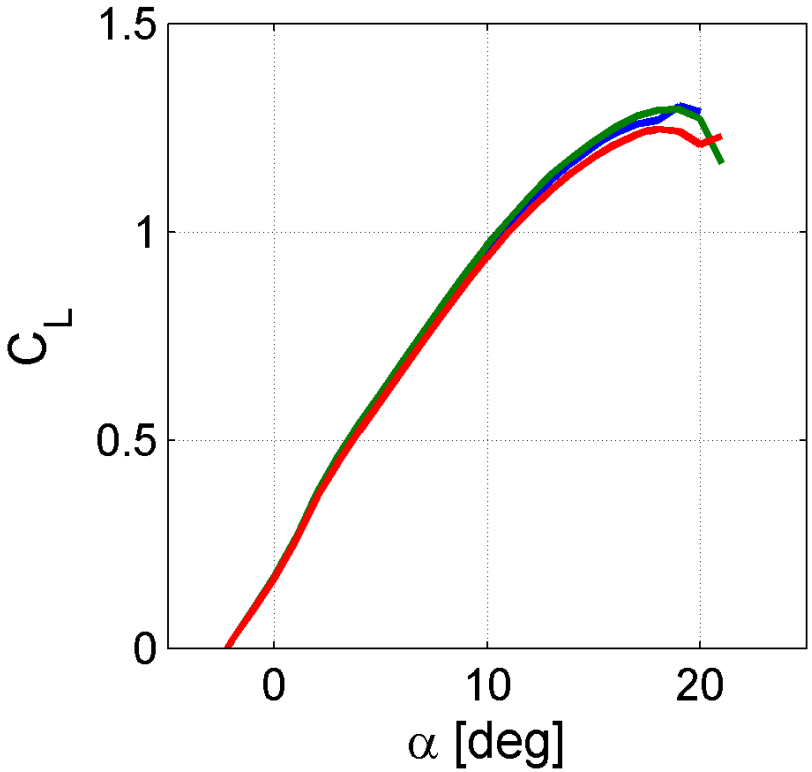
AR: 16

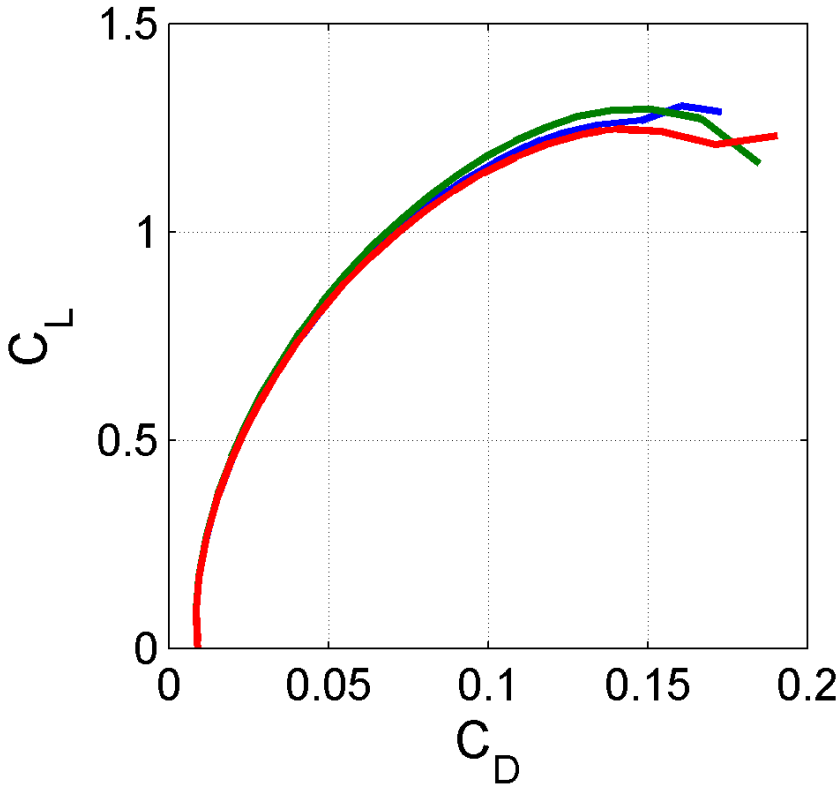
B767

AR: 8

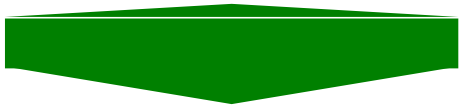
wikipedia.org

Afilamento

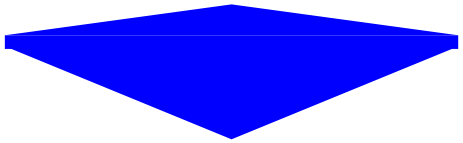




NACA 2412 wing
Re 3e5; AR=6; λ=1.0
Non-linear LLT

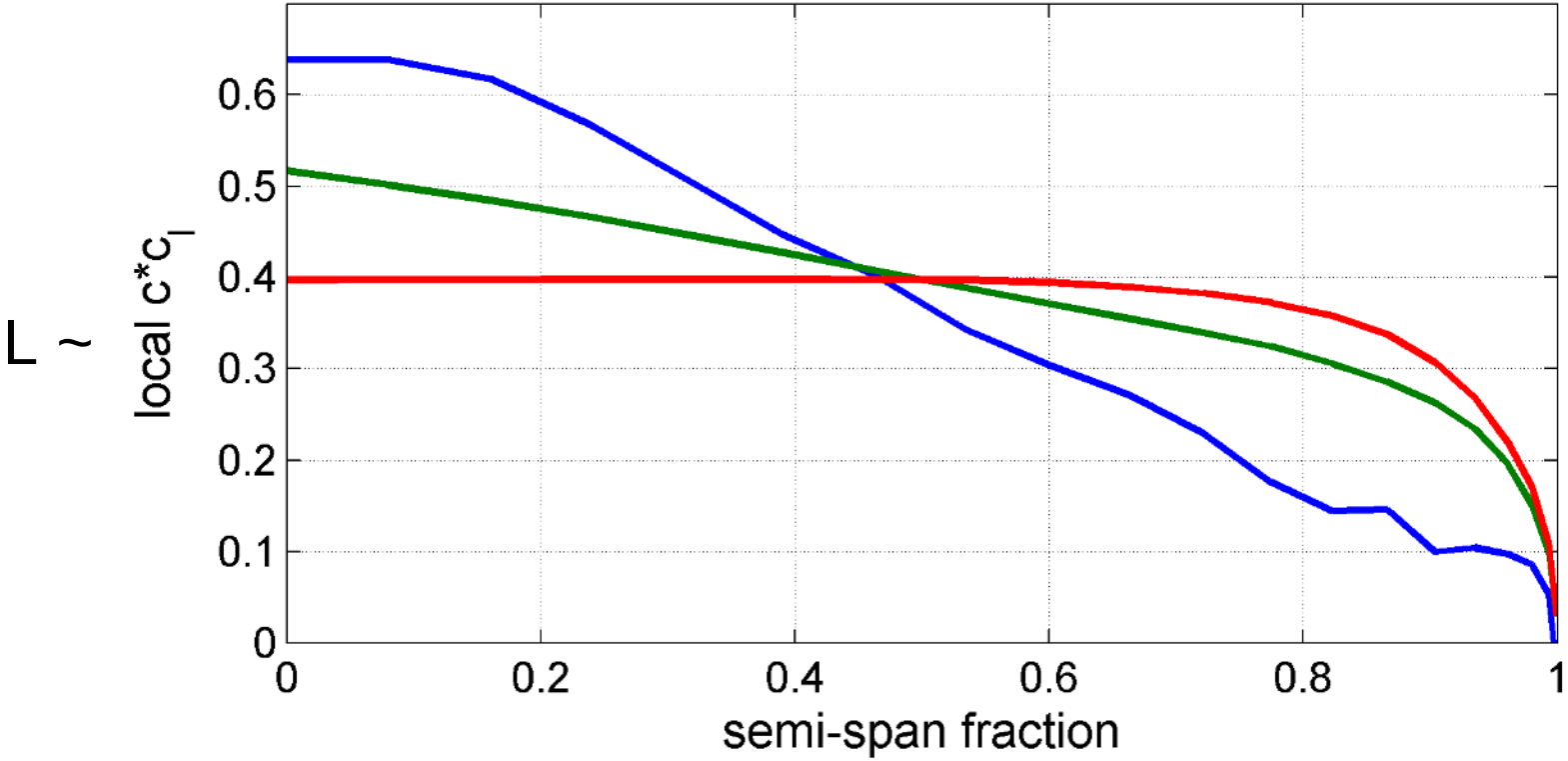


NACA 2412 wing
Re 3e5; AR=6; λ=0.5
Non-linear LLT

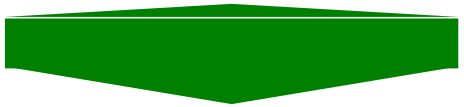


NACA 2412 wing
Re 3e5; AR=6; λ=0.1
Non-linear LLT

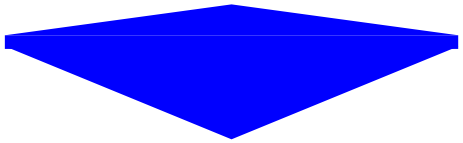
Afilamento



NACA 2412 wing
Re 3e5; AR=6; λ=1.0
Non-linear LLT

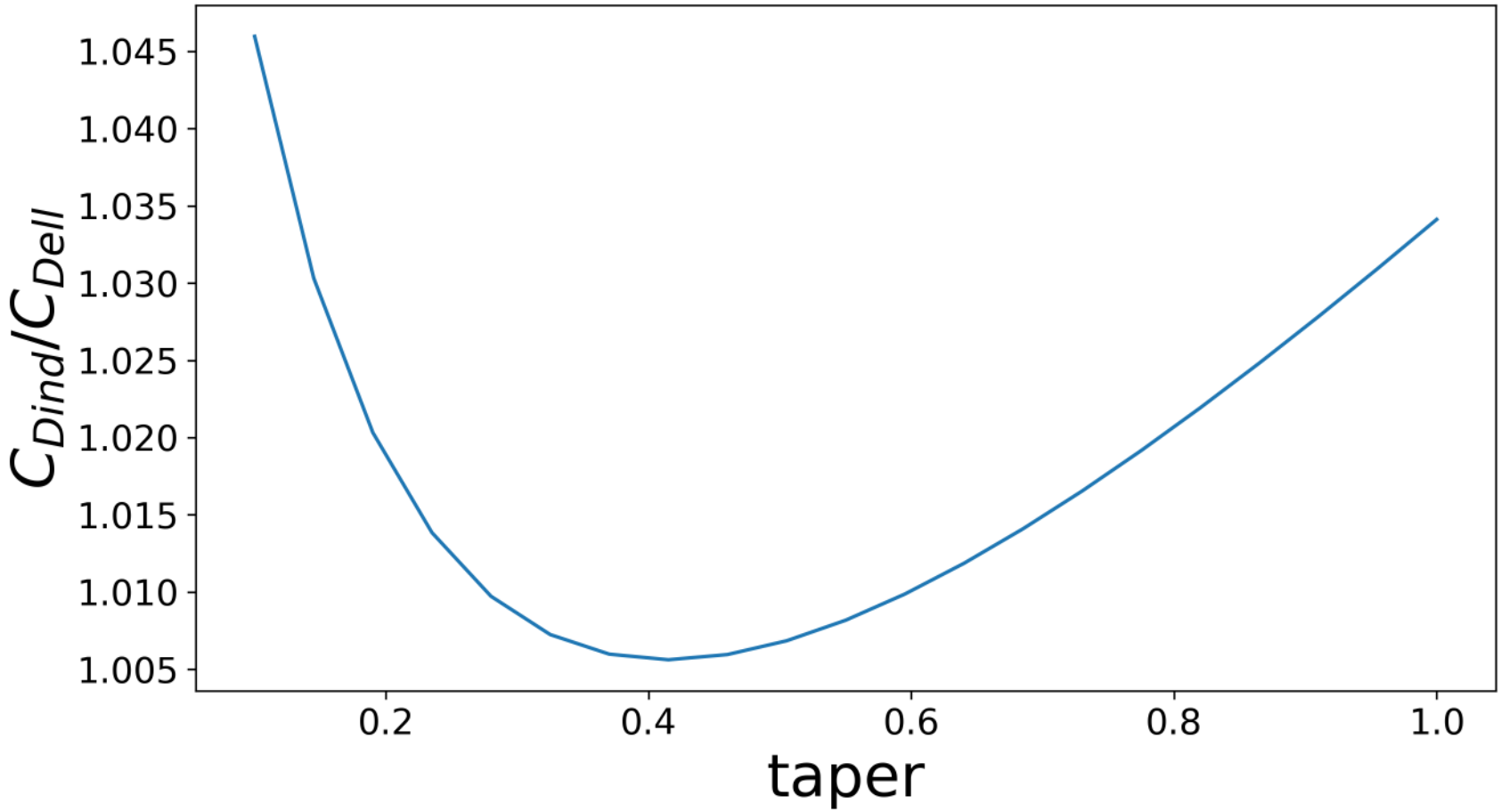


NACA 2412 wing
Re 3e5; AR=6; λ=0.5
Non-linear LLT



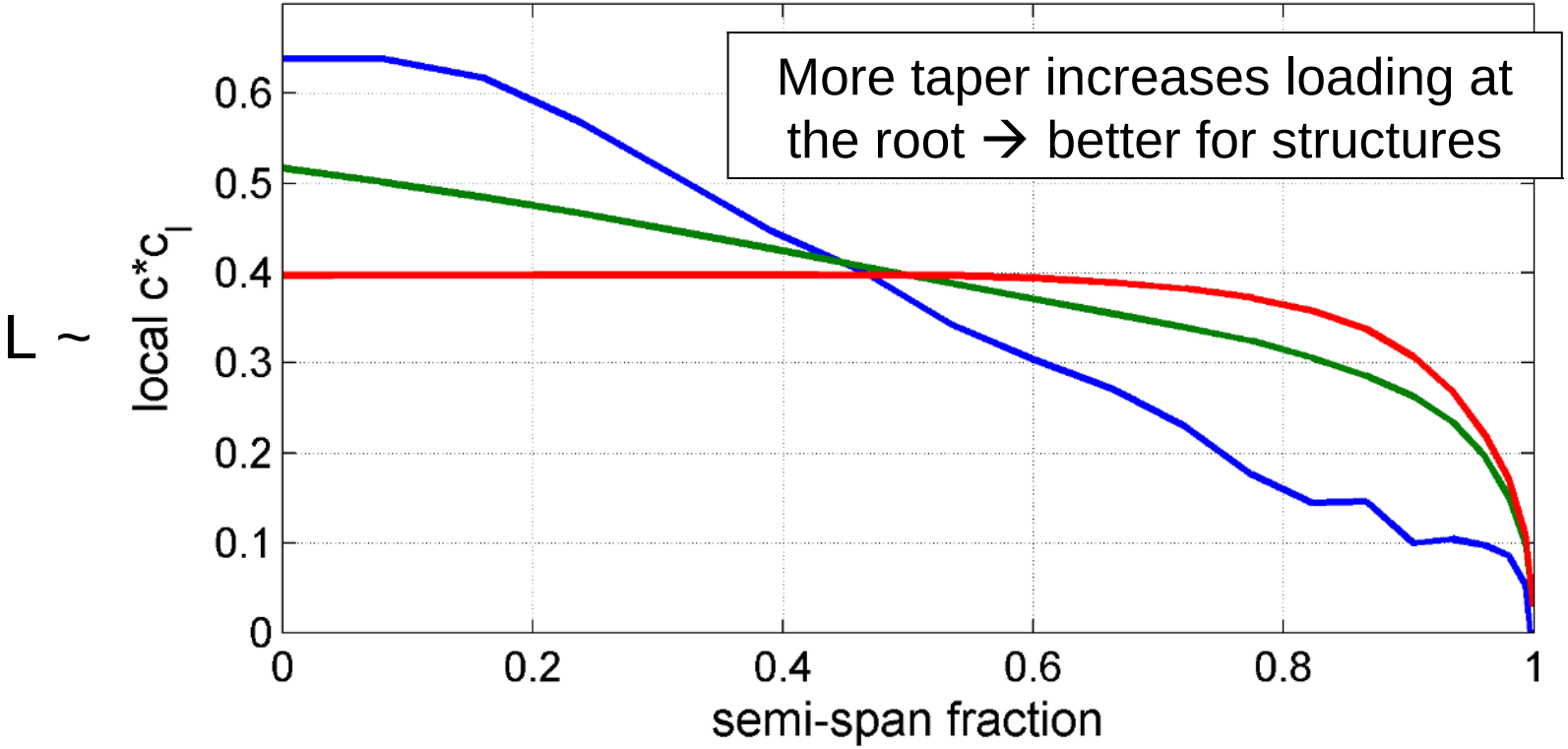
NACA 2412 wing
Re 3e5; AR=6; λ=0.1
Non-linear LLT

Afilamento

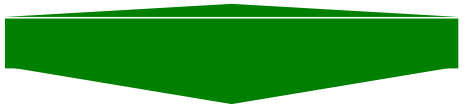


AR = 8.0 CL = 0.5

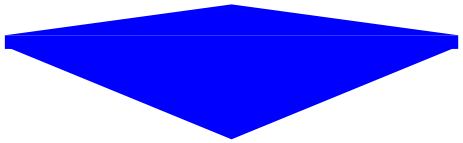
Afilamento



NACA 2412 wing
Re 3e5; AR=6; λ=1.0
Non-linear LLT

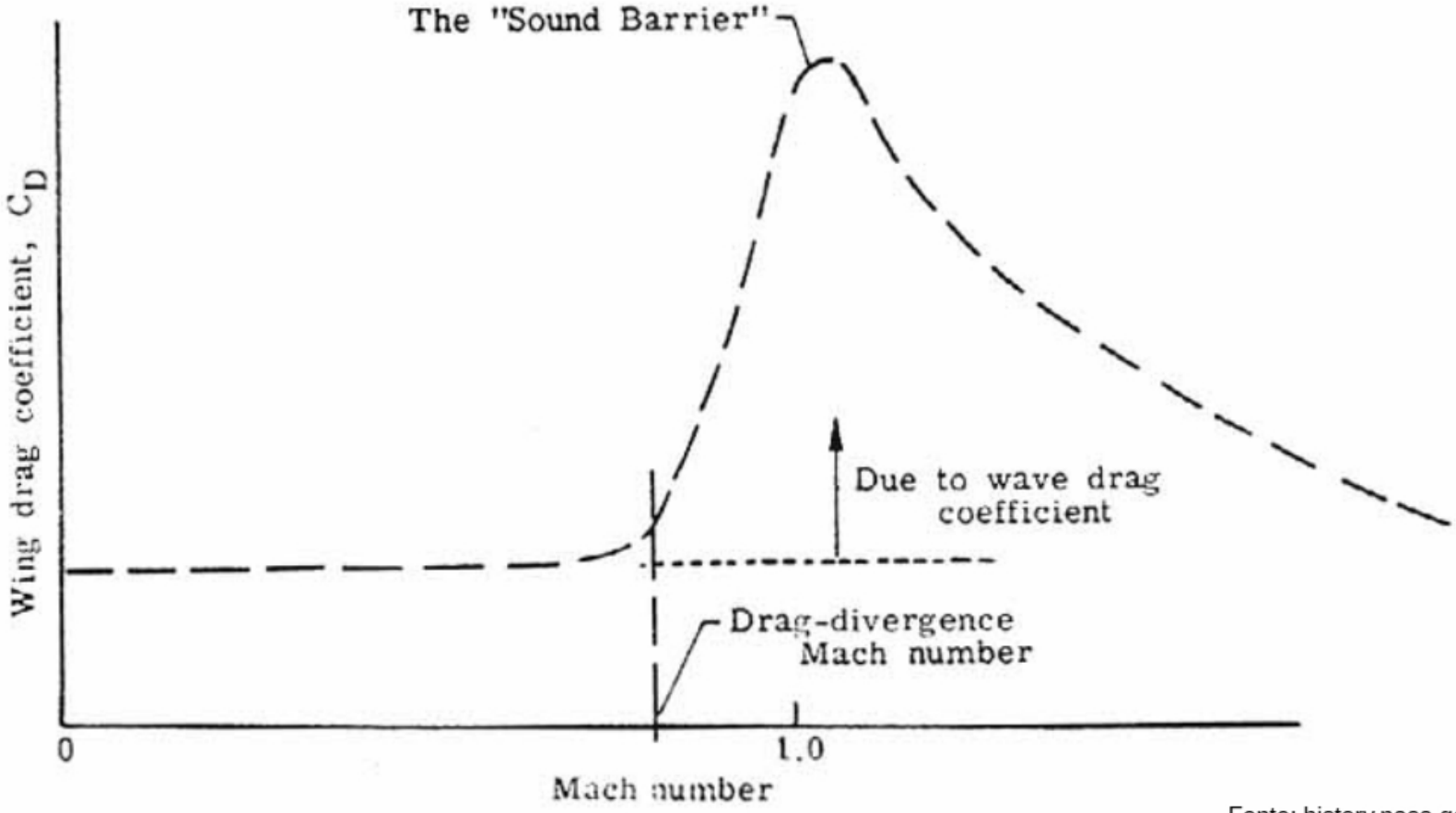


NACA 2412 wing
Re 3e5; AR=6; λ=0.5
Non-linear LLT



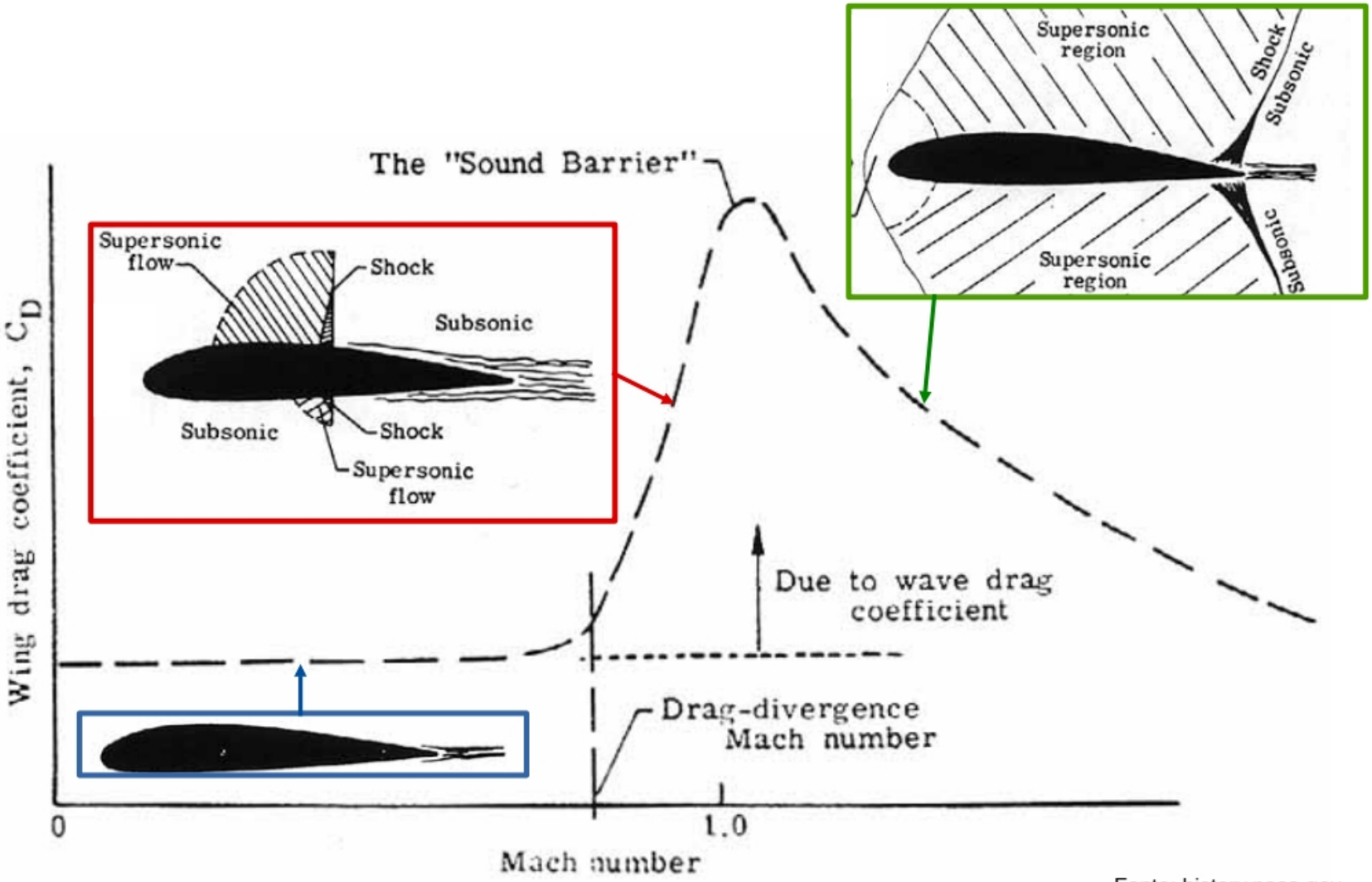
NACA 2412 wing
Re 3e5; AR=6; λ=0.1
Non-linear LLT

Ondas de choque causam o aumento de arrasto em altas velocidades



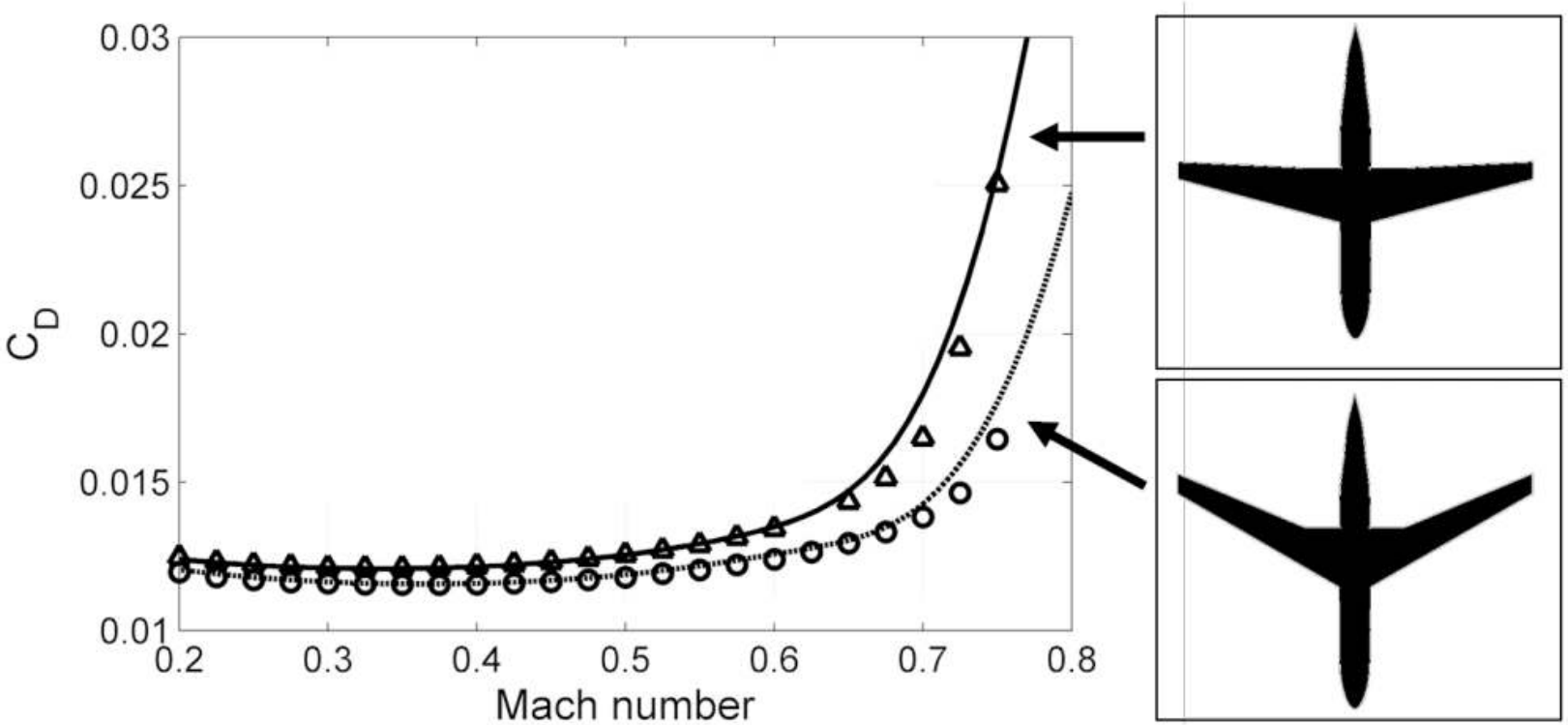
Fonte: history.nasa.gov

Ondas de choque causam o aumento de arrasto em altas velocidades



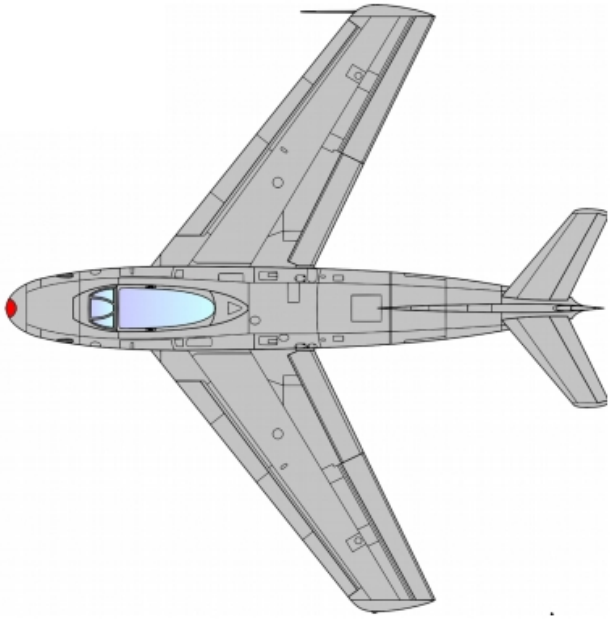
Fonte: history.nasa.gov

O enflechamento pode retardar a divergência do arrasto



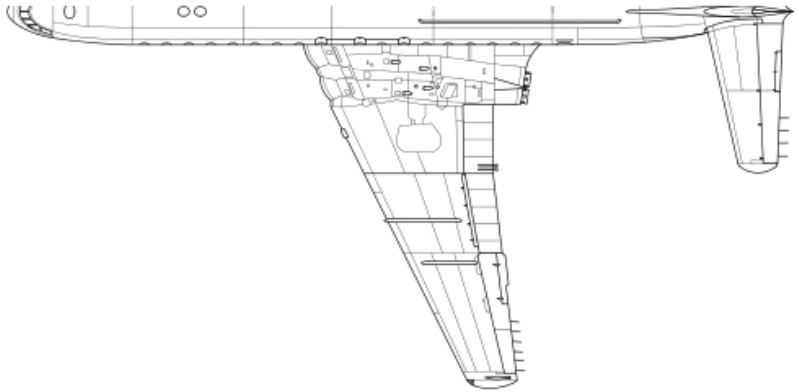
Secco, Mattos, 2017

Aeronaves passaram a ter asas cada vez mais enflechadas

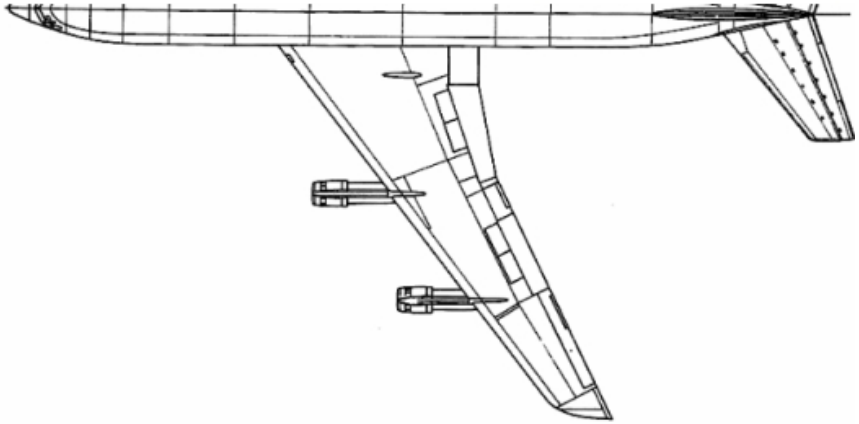
Supermarine Spitfire	Messerschmitt 262	F-86 Sabre
		
Ano: 1938	Ano: 1944	Ano: 1953
Motor: Pistão	Motor: Jato	Motor: Jato
Enflechamento: 0 graus	Enflechamento: 18 graus	Enflechamento: 35 graus
Velocidade: 322 nós	Velocidade: 528 nós	Velocidade: 583 nós

Essa tendência também passou para a aviação comercial

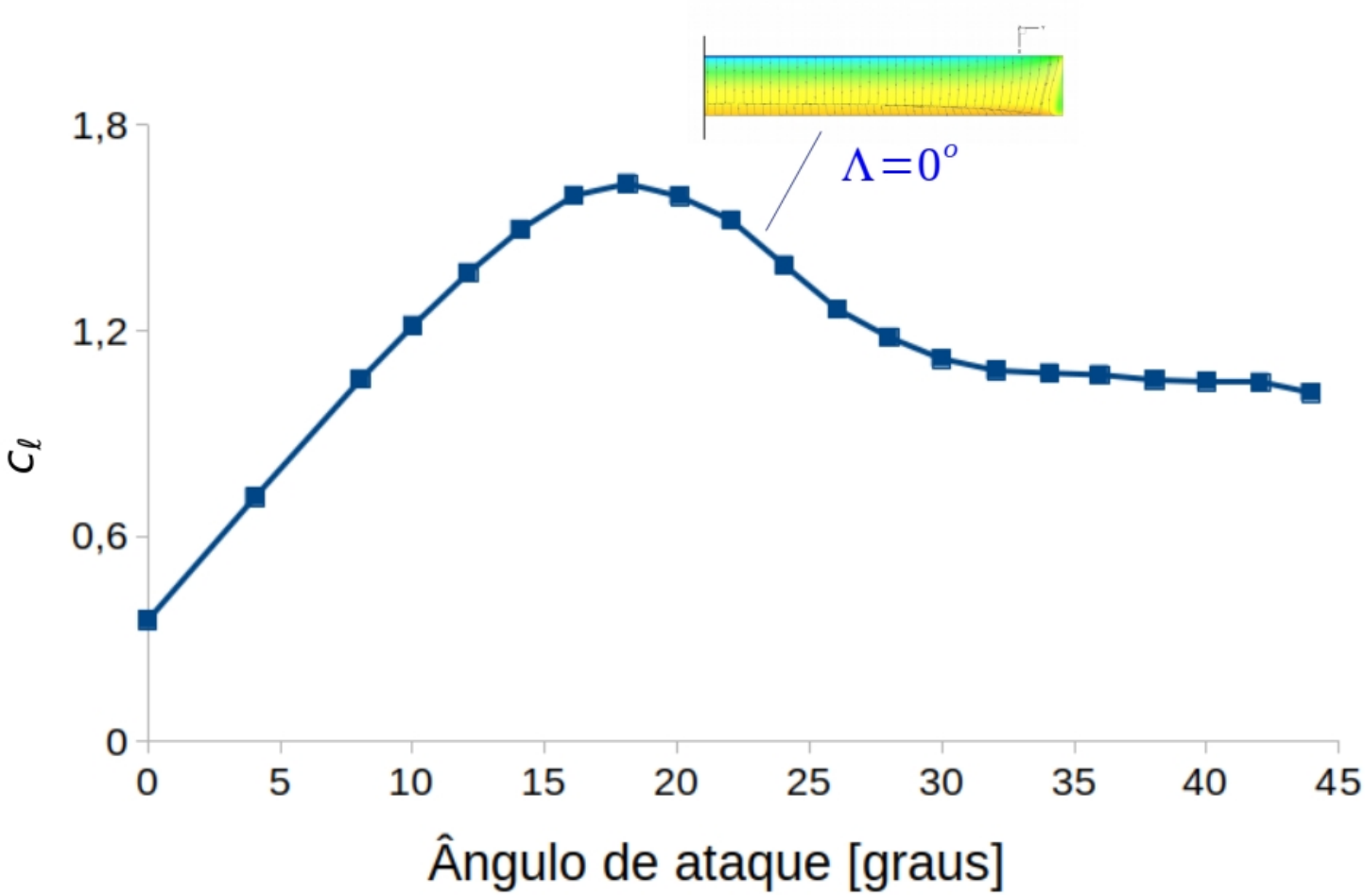
De Havilland Comet
1952 – 1975



Boeing 707
1957 – 1979

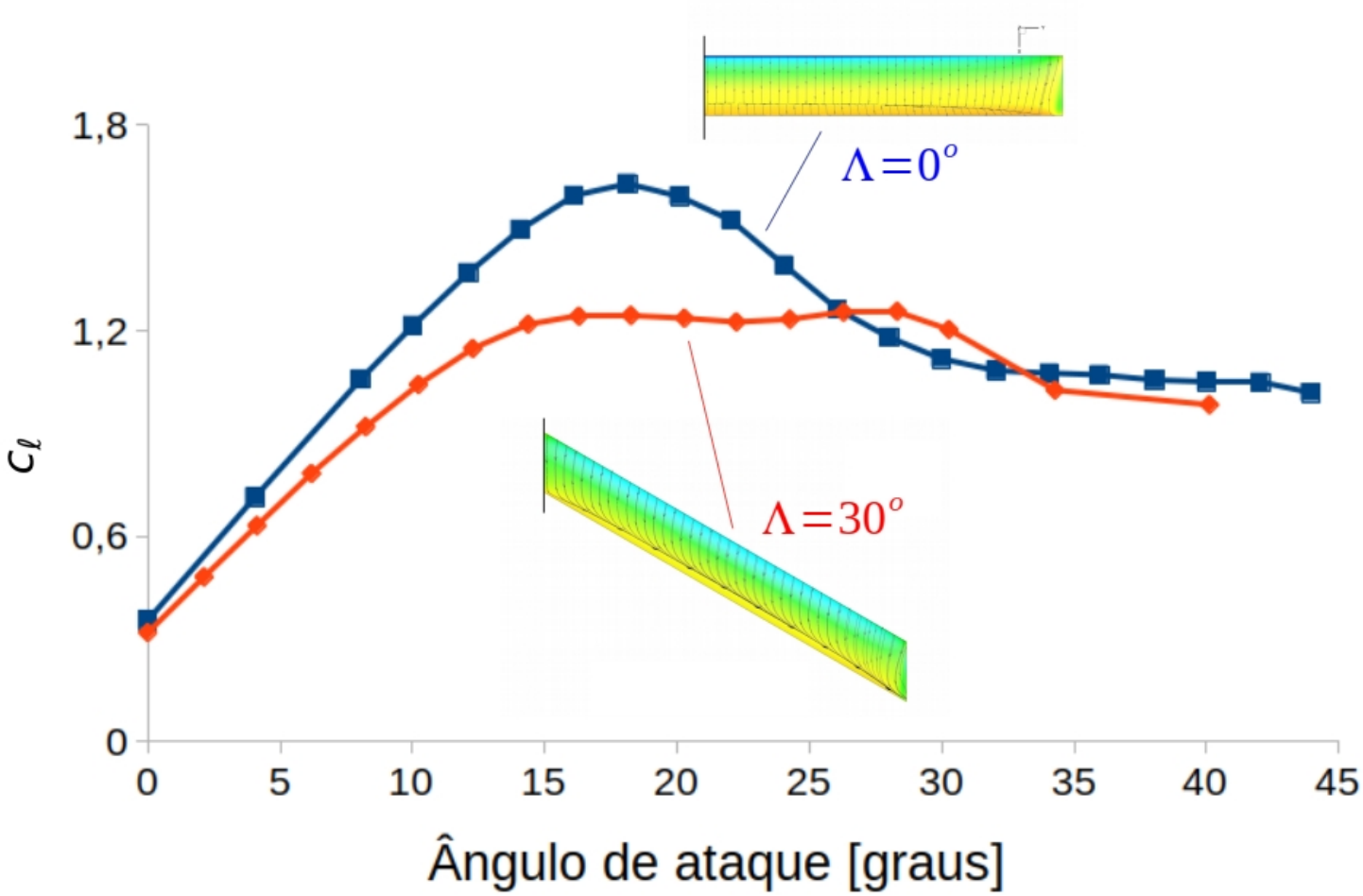


Asas enflechadas geram menos sustentação



Petrilli, Paul, Gopalarathnam, 2014

Asas enflechadas geram menos sustentação



Petrilli, Paul, Gopalarathnam, 2014

Asas de enflechamento variável fornecem características aerodinâmicas adequadas para diferentes fases de voo

F-14 Tomcat

Baixa velocidade

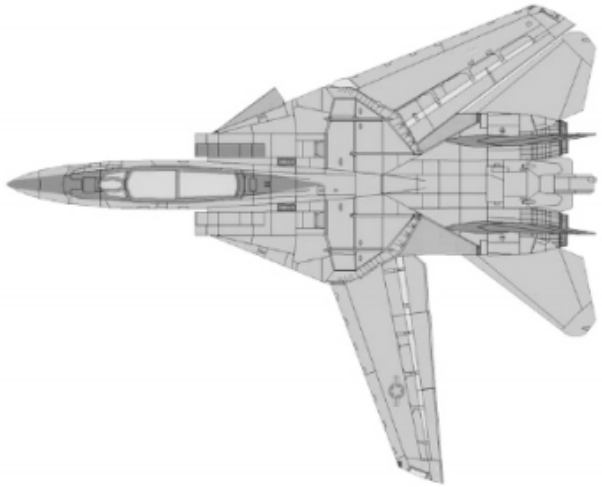
Alta velocidade

Ano: 1974 – 2006

Velocidade: Mach 2,3 (2400 km/h)

Altitude máxima: 50000 ft

Raio de combate: 900 km



Aeronaves de asa oblíqua já foram testadas

NASA AD-1

wikipedia.org

Aeronaves de asa oblíqua já foram testadas

NASA AD-1

wikipedia.org

- Rótula da asa simplificada
- Menor variação de CG e Ponto Neutro
- Melhor distribuição de volume para arrasto de onda
- Assimetria frente à rajadas e também pelo espessamento da camada limite na asa traseira

A progressão do estol depende da forma em planta

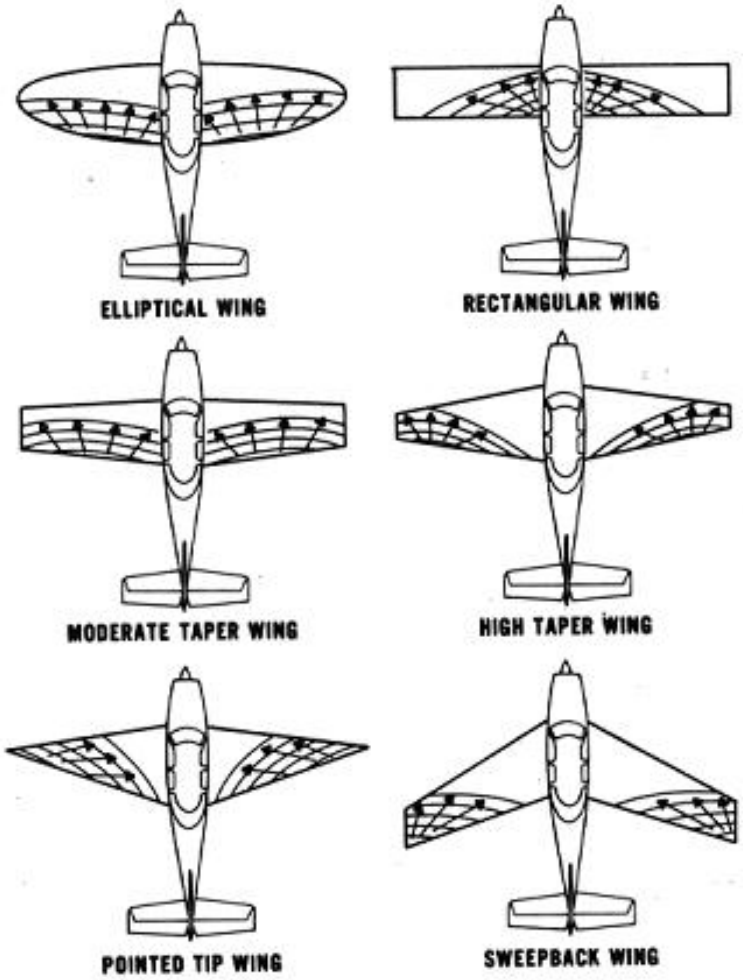


Figure 17–13 Wing Planforms (Exaggerated)

Afilamento maior que 1.0 traz o estol para a raiz da asa

XF-91 Thunderceptor

wikipedia.org

- Asa de incidência variável
- Trem retraía na direção da ponta da asa

Há aeronaves com enflechamento negativo

wikipedia.org

Su-47

X-29

nasa.gov

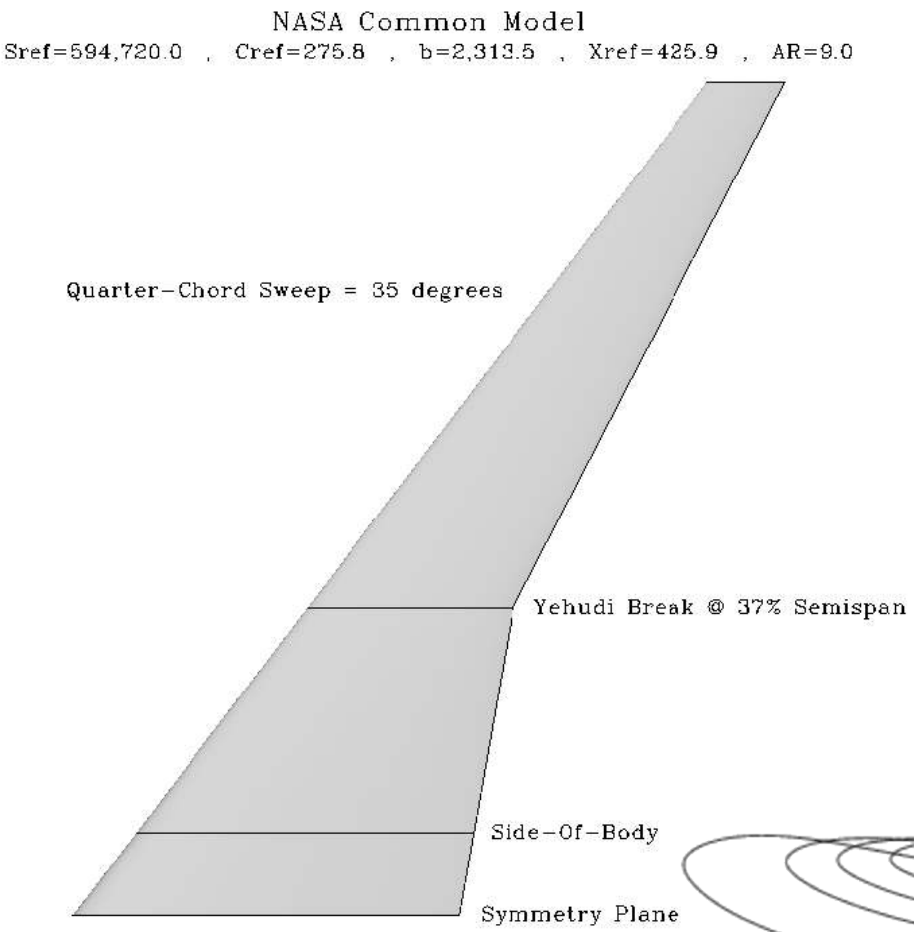
NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: EC87-0182-14 Date: July 24, 1987 Photo By: NASA

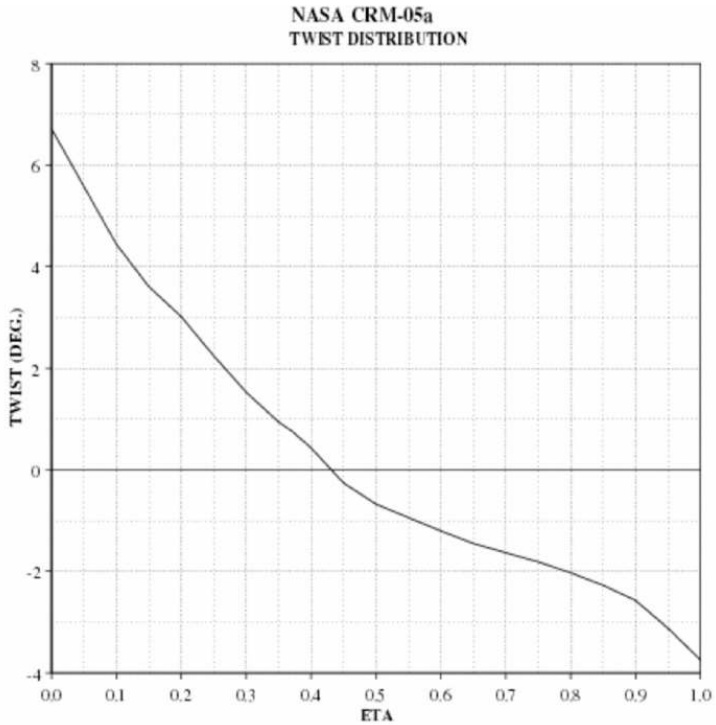
X-29 in Banked Flight

Hansa Jet

globalsecurity.org

Torção na asa é outra maneira de se evitar estol de ponta





Vassberg, et. al., 2008

Tendências gerais

- Maior Alongamento
  - Menor arrasto induzido
  - Maior $c_{\ell max}$
  - Maior peso estrutural
  - Maior tendência para problemas aeroelásticos
- Maior Afilamento (menor λ)...
  - Menor arrasto induzido (até valores intermediários de λ)
  - Menor peso estrutural
  - Maior tendência para estol de ponta
- Maior Enflechamento
  - Menor arrasto de onda
  - Menor tendência para problemas aeroelásticos
  - Menor $c_{\ell max}$
  - Maior tendência para estol de ponta
  - Melhor estabilidade látero-direcional
  - Maior tendência para pitch-up

Projeto de superfícies aerodinâmicas

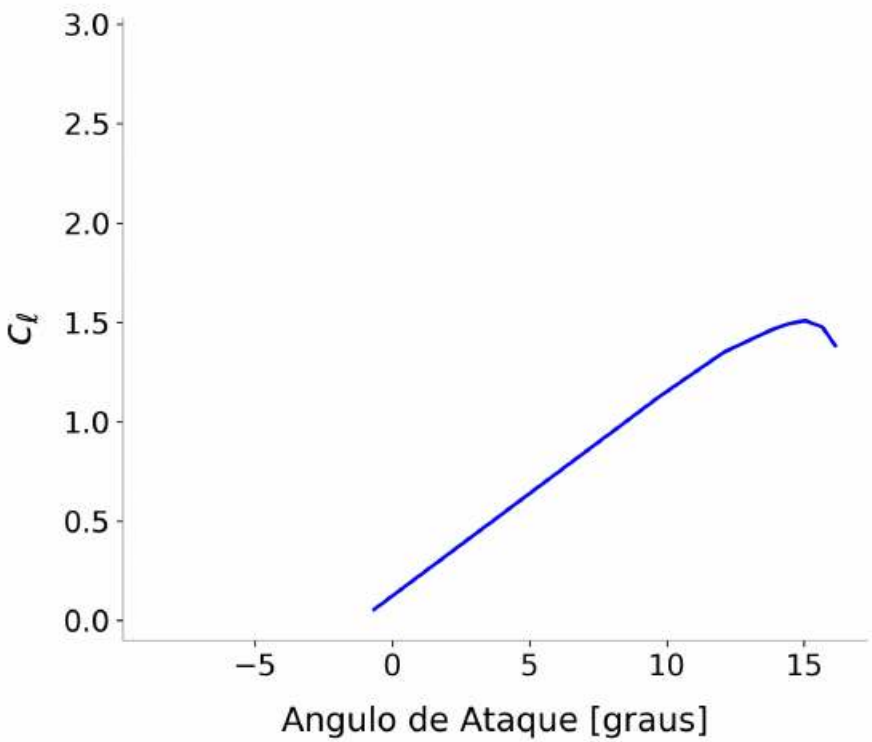
- Seleção de aerofólios
- Definição de forma em planta
- Dispositivos de hiper-sustentação
- Dispositivos de controle

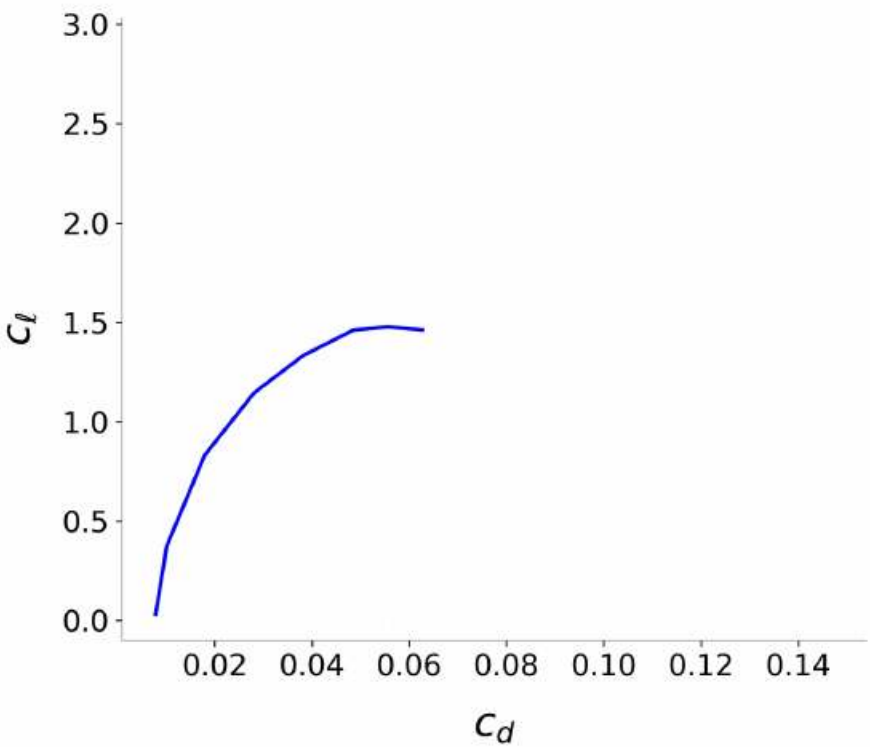
Hiper-sustentadores podem estar nos dois bordos da asa

B747

Adrian Pingstone, Public Domain

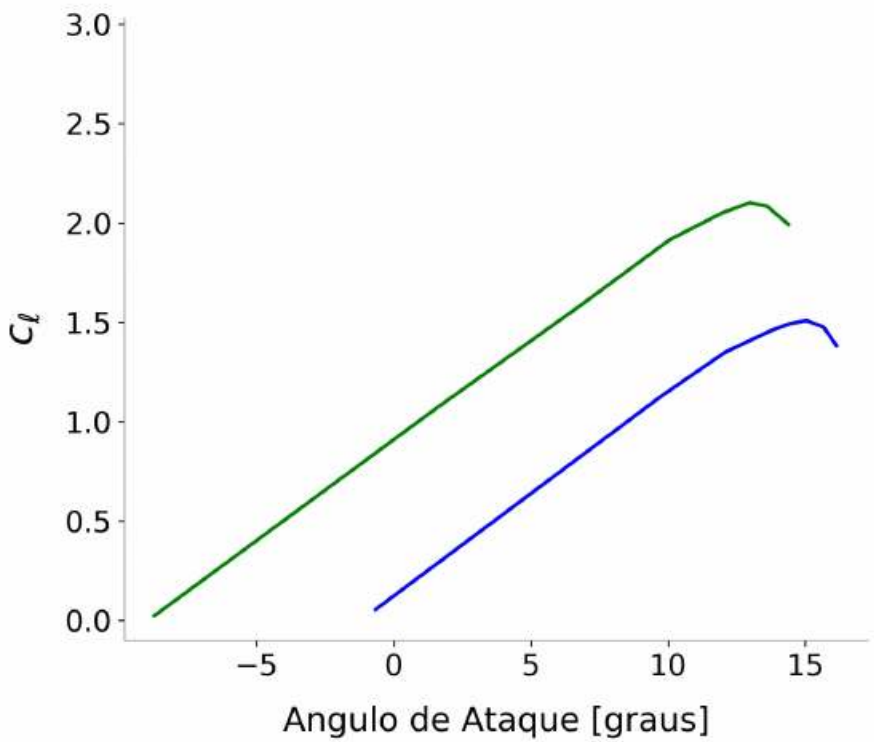
Dispositivos hiper-sustentadores aumentam o máximo coeficiente de sustentação

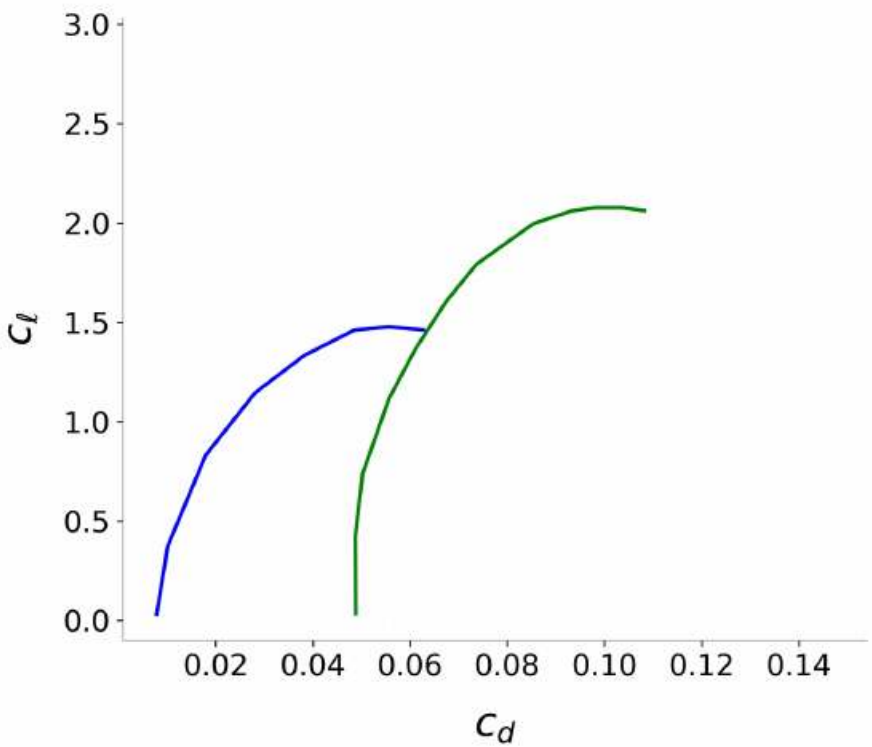


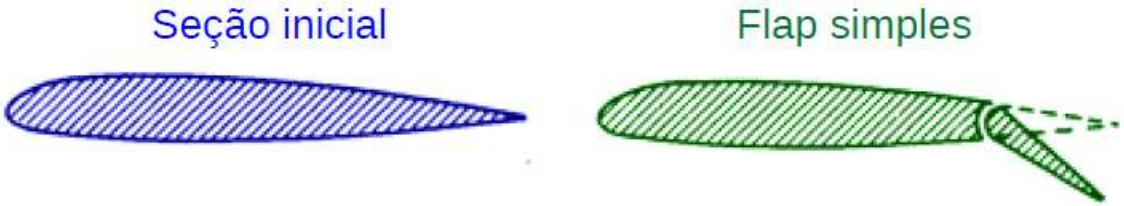


Seção inicial

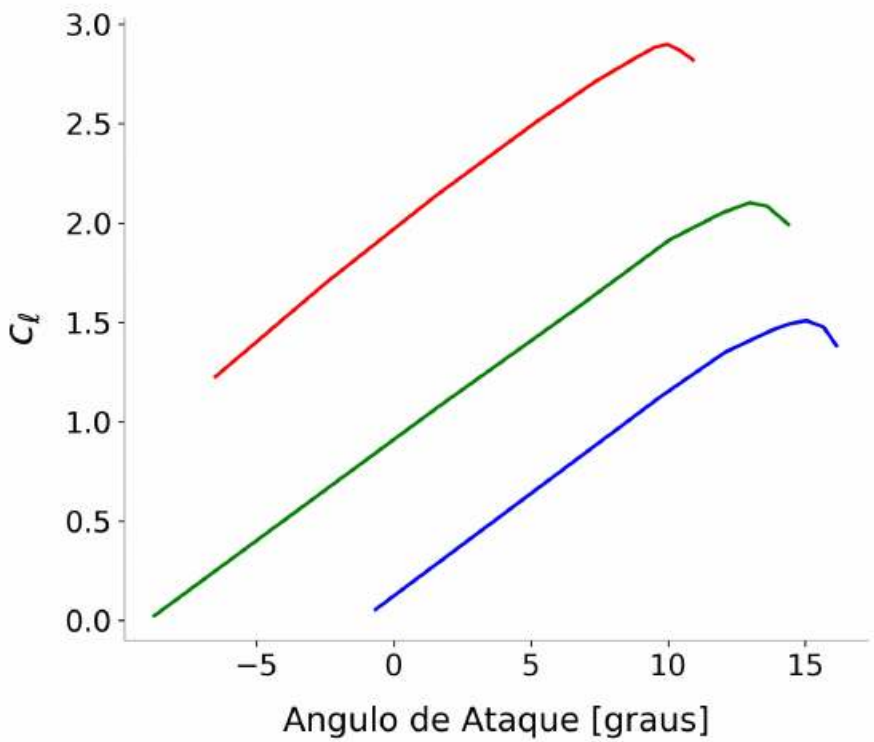
Dispositivos hiper-sustentadores aumentam o máximo coeficiente de sustentação

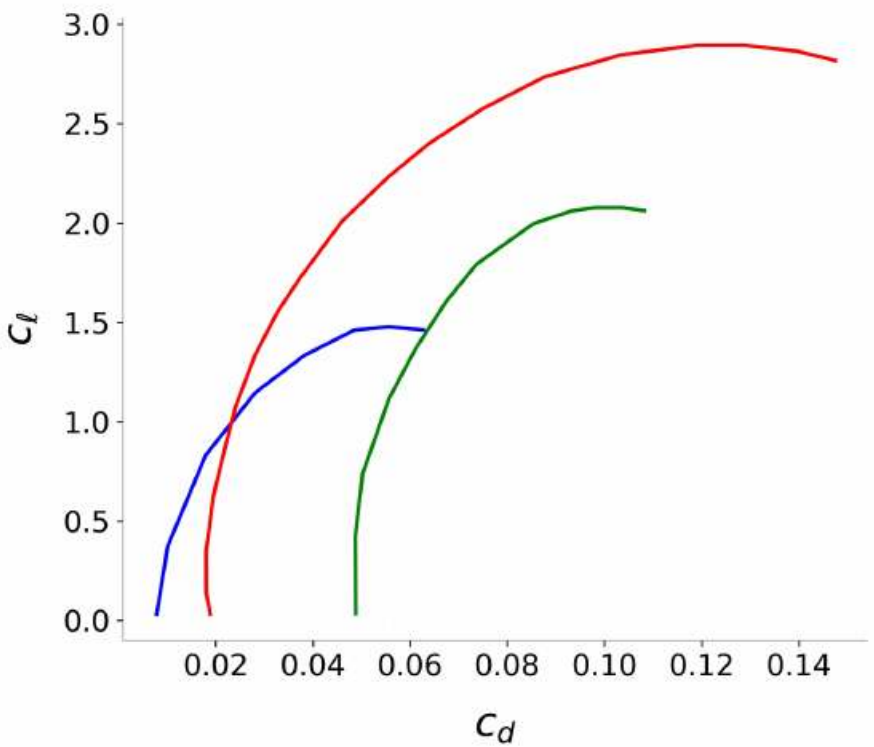


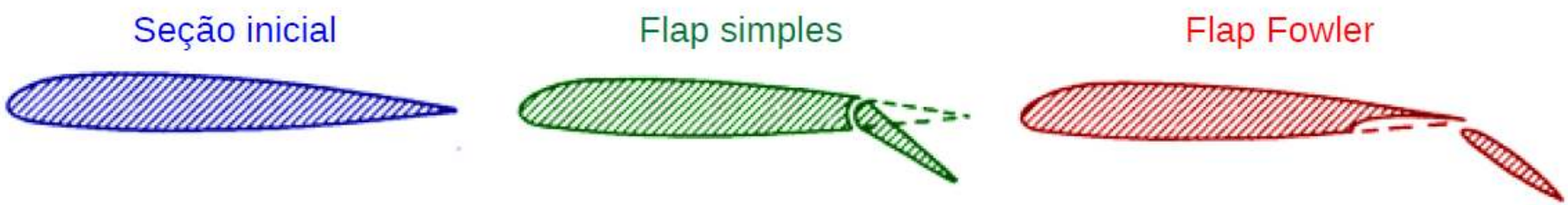




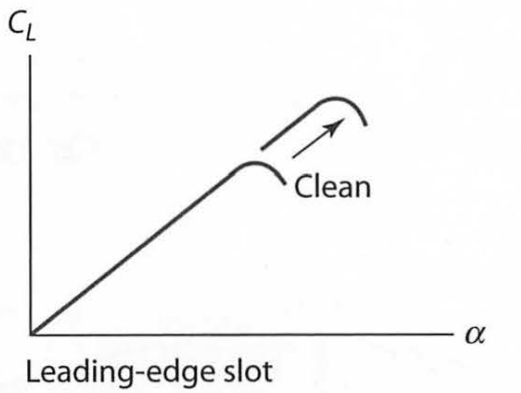
Dispositivos hiper-sustentadores aumentam o máximo coeficiente de sustentação



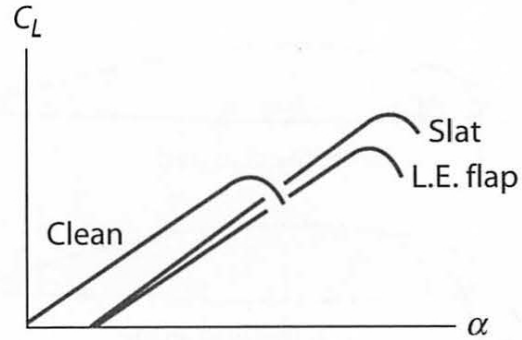




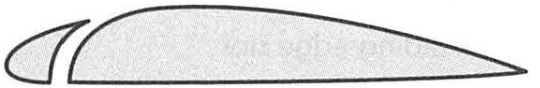
Hiper-sustentadores também podem ser instalados no bordo de ataque



Leading-edge slot

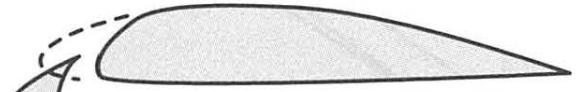


Leading-edge flap or slat

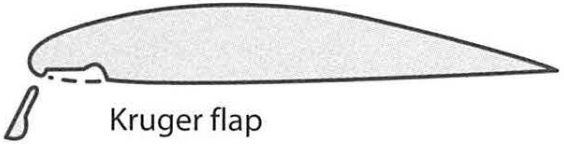


Leading-edge slot

Leading-edge flap



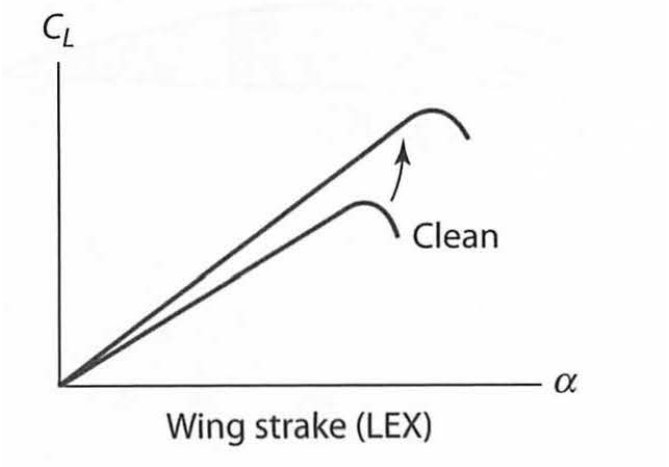
Slotted leading-edge flap (slat)



Kruger flap

Raymer

Strakes de bordo de ataque também ajudam a aumentar a sustentação



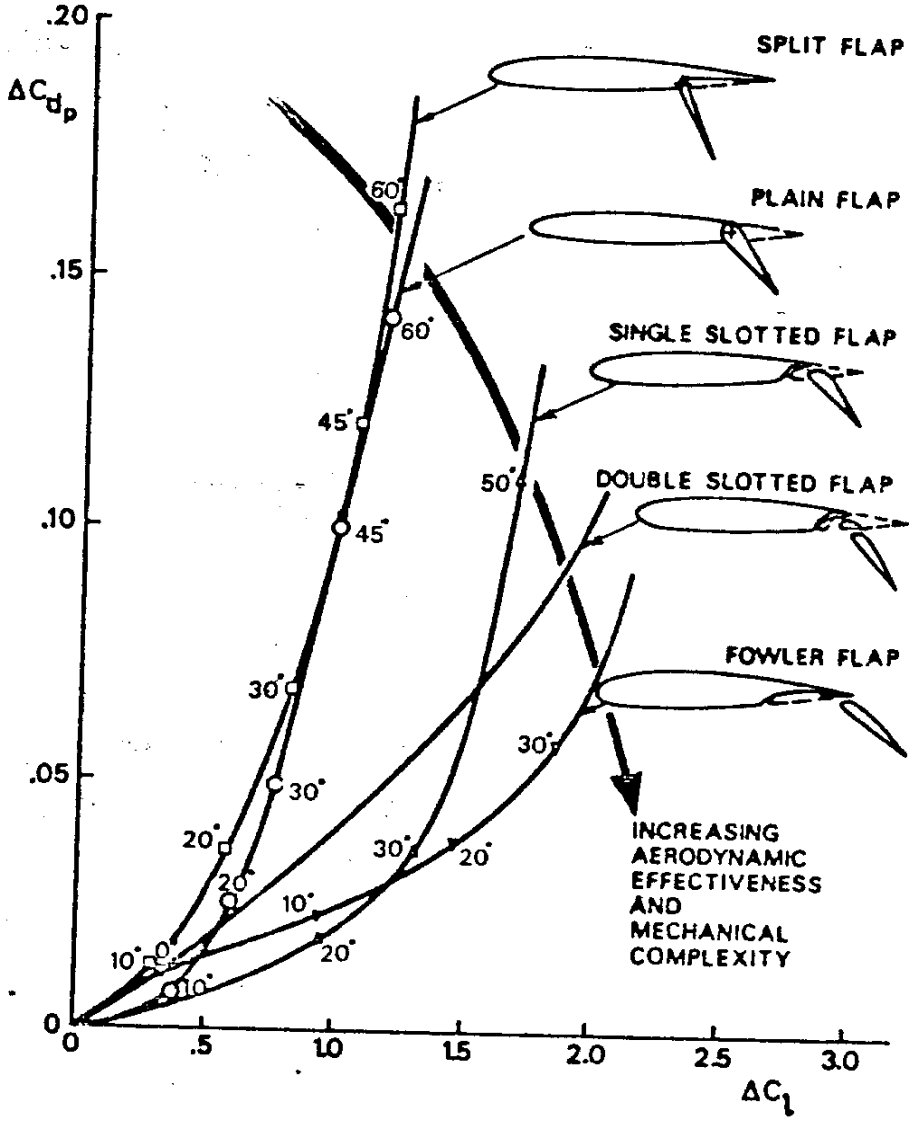
Raymer

Dryden Flight Research Center EC95 43249-2 Photographed 8/95
F-18 HARV: Actuated Nose Strakes for Enhanced Rolling (ANSER)
Hinged nose strakes are opened to produce large side forces for control.

nasa.gov

F-18

Aumento de sustentação está atrelado ao aumento de arrasto



Projeto de superfícies aerodinâmicas

- Seleção de aerofólios
- Definição de forma em planta
- Dispositivos de hiper-sustentação
- Dispositivos de controle

Projeto de superfícies aerodinâmicas

- Seleção de aerofólios
- Definição de forma em planta
- Dispositivos de hiper-sustentação
- Dispositivos de controle

Espere até a aula de controle!

Fuselagem mais esbelta tem um arrasto menor

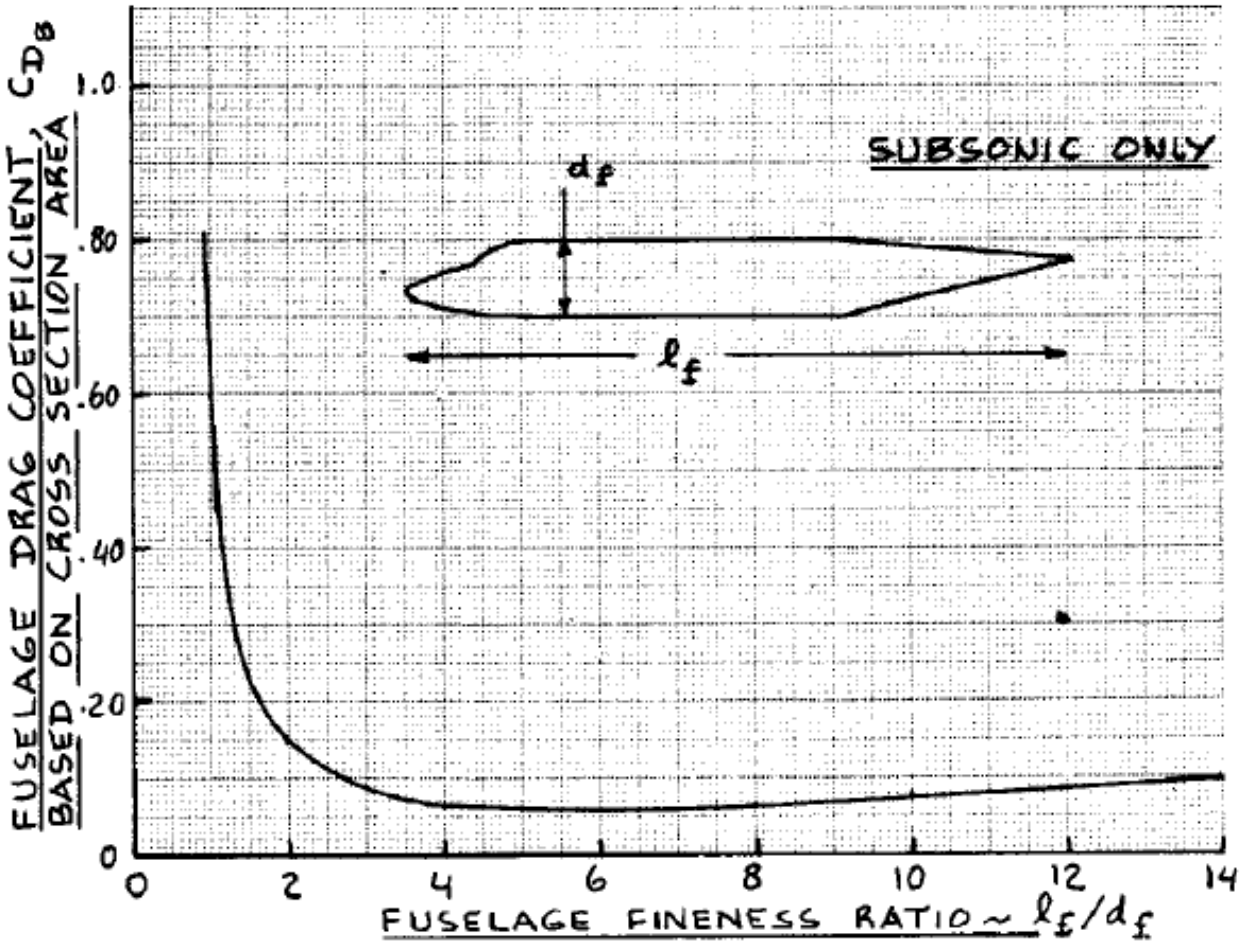


Figure 3.1 Effect of Fineness Ratio on Fuselage Drag

Roskam

O ângulo do cone de cauda e a área de base também são fontes de arrasto

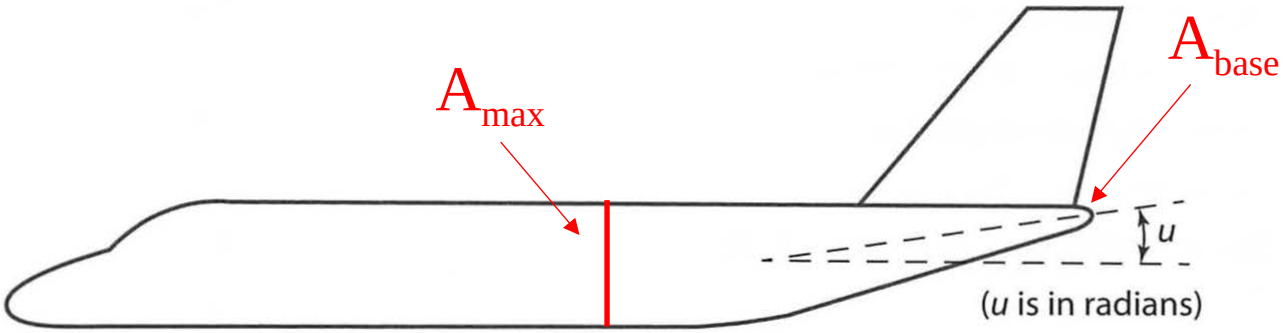


Fig. 12.27 Fuselage upsweep.

Raymer

Arrasto de inclinação

$$D/q_{\text{upsweep}} = 3.83u^{2.5}A_{\max}$$

Arrasto de base

Subsonic:

$$(D/q)_{\text{base}} = [0.139 + 0.419(M - 0.161)^2]A_{\text{base}}$$

Supersonic:

$$(D/q)_{\text{base}} = [0.064 + 0.042(M - 3.84)^2]A_{\text{base}}$$

M = número de Mach

Aeronaves com rampa traseira podem resultar em fuselagens com alto arrasto

C-130

Adrian Pingstone, wikipedia.org

Há outras fontes de arrasto

- Nacelles
- Motores inoperantes
- Trens de pouso
- Antenas
- Gaps
- Demais protuberâncias
- DATCOM

Estimating a drag polar

- For now, our drag polar will have the form:

Parabolic drag polar

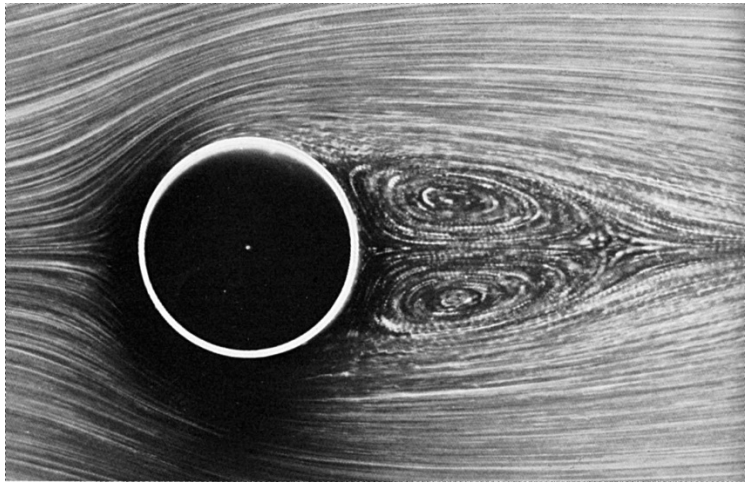
$$C_D(C_L) = C_{D0} + KC_L^2$$

Stall!!!

For $C_L < C_{Lmax}$

Parasite drag
Friction
Separation

Induced drag
3D effects
Wingtip vortices



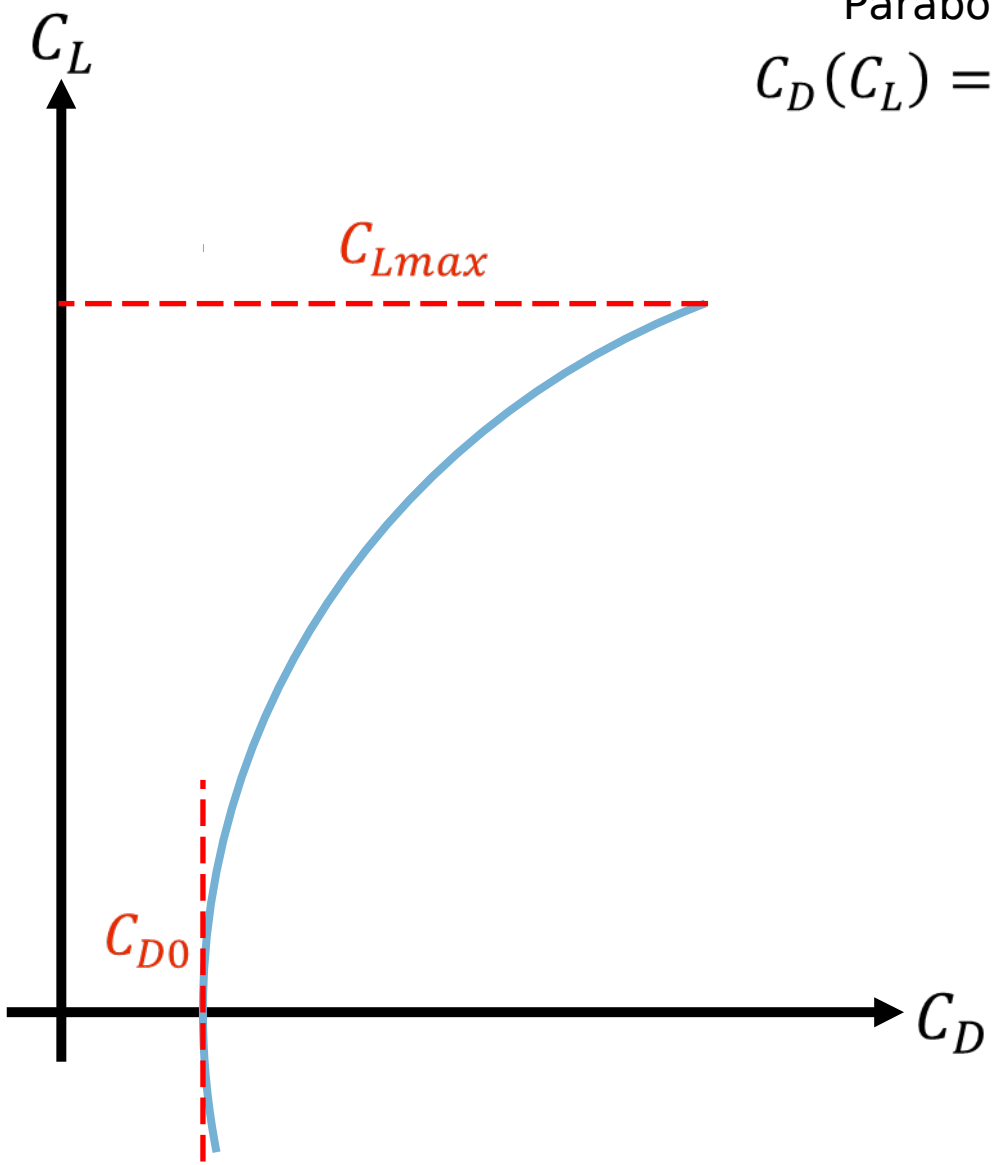
Van Dyke, 1982

en.wikipedia.org

Estimating a drag polar

Parabolic drag polar

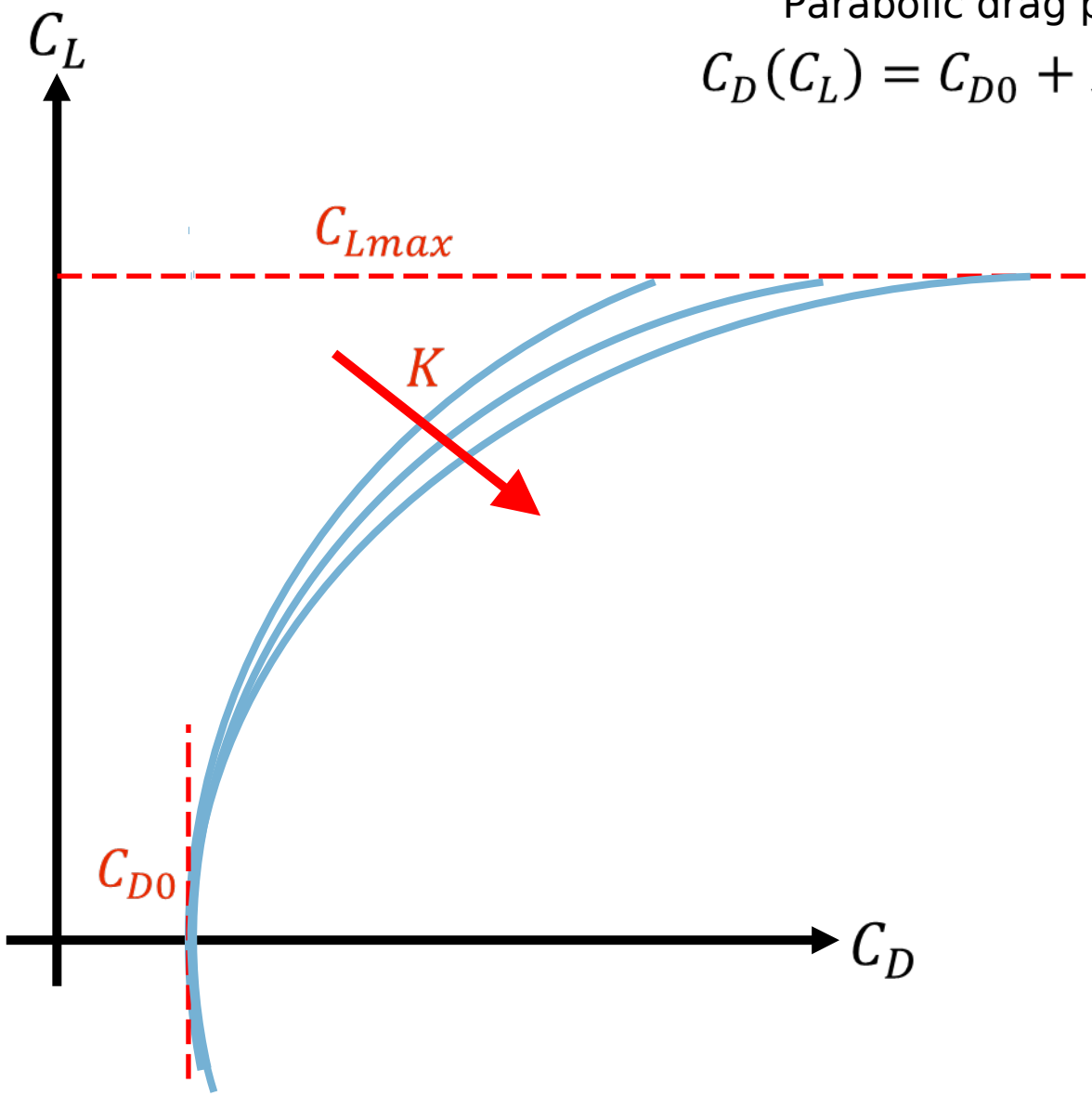
$$C_D(C_L) = C_{D0} + KC_L^2 \quad \boxed{\text{For } C_L < C_{Lmax}}$$



Estimating a drag polar

Parabolic drag polar

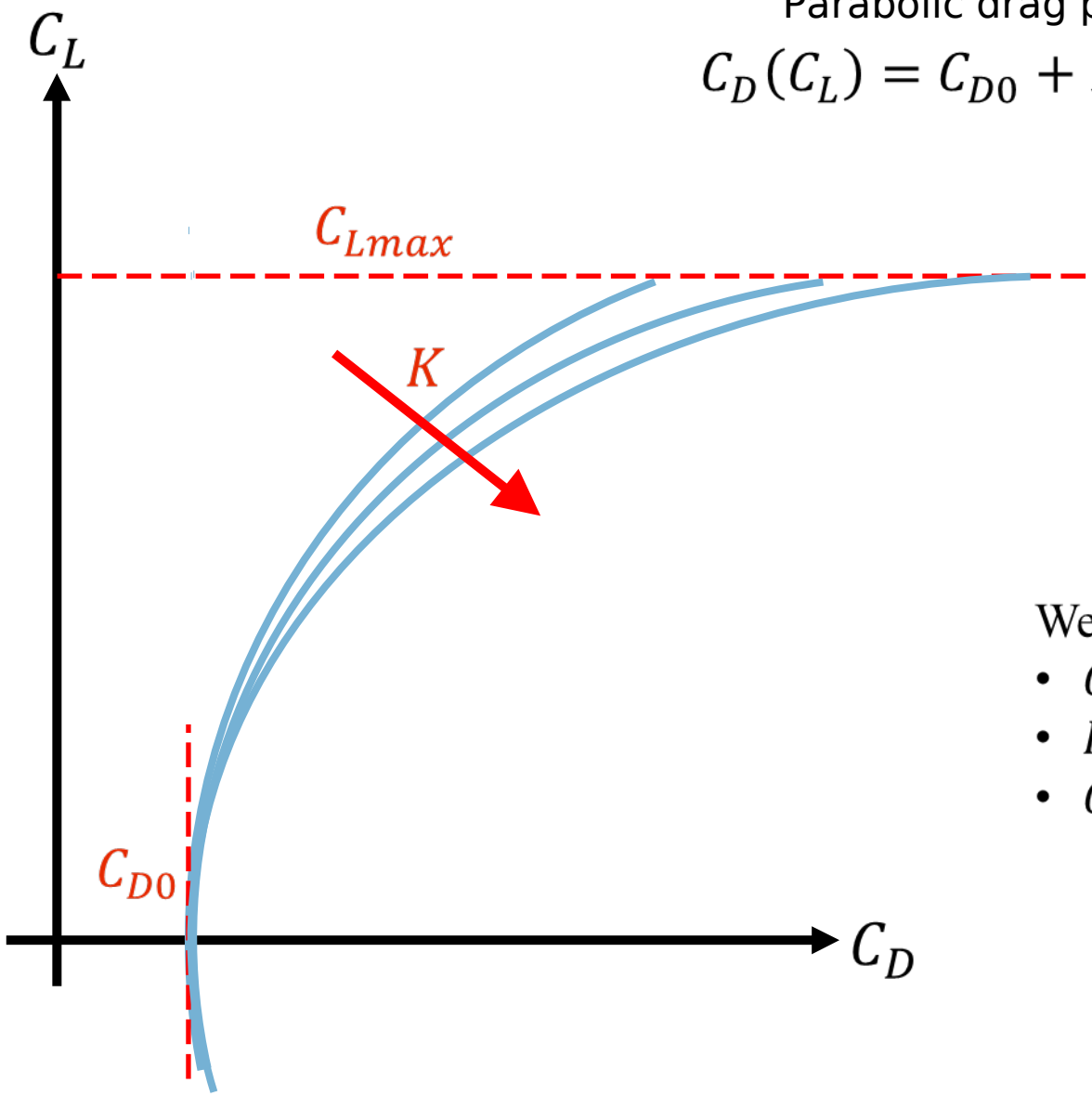
$$C_D(C_L) = C_{D0} + KC_L^2 \quad \boxed{\text{For } C_L < C_{Lmax}}$$



Estimating a drag polar

Parabolic drag polar

$$C_D(C_L) = C_{D0} + KC_L^2 \quad \boxed{\text{For } C_L < C_{Lmax}}$$



We need to estimate:

- C_{D0}
- K
- C_{Lmax}

The Class 2 Method considers pressure drag and interference drag as well

- We add drag coefficients from all components:

$$C_{D0} = \sum_i C_{f,i} \cdot F_i \cdot Q_i \cdot \frac{S_{wet,i}}{S_{ref}}$$

Friction coefficient

Form factor

Interference factor

Wetted area expressions

- Aerodynamic surfaces

$$S_{wet,w} = 2 \cdot S_{exp,w} \cdot \left(1 + \frac{(t/c)_{r,w}}{4 \cdot (1+\lambda_w)} \cdot \left(1 + \lambda_w \cdot \frac{(t/c)_{r,w}}{(t/c)_{t,w}}\right)\right) \qquad S_{exp,w} = S_w - c_{r,w} \cdot D_f$$

$$S_{wet,h} = 2 \cdot S_{exp,h} \cdot \left(1 + \frac{(t/c)_{r,h}}{4 \cdot (1+\lambda_h)} \cdot \left(1 + \lambda_h \cdot \frac{(t/c)_{r,h}}{(t/c)_{t,h}}\right)\right) \qquad S_{exp,h} = S_h$$

$$S_{wet,v} = 2 \cdot S_{exp,v} \cdot \left(1 + \frac{(t/c)_{r,v}}{4 \cdot (1+\lambda_v)} \cdot \left(1 + \lambda_v \cdot \frac{(t/c)_{r,v}}{(t/c)_{t,v}}\right)\right) \qquad S_{exp,v} = S_v$$

- Fuselage

$$S_{wet,f} = \pi \cdot D_f \cdot L_f \cdot \left(1 - \frac{2}{\lambda_f}\right)^{2/3} \cdot \left(1 + \frac{1}{\lambda_f^2}\right) \qquad \lambda_f = \frac{L_f}{D_f}$$

- Nacelle

$$S_{wet,n} = n_{eng} \cdot \pi \cdot D_n \cdot L_n$$

- Total wetted area

$$S_{wet} = S_{wet,w} + S_{wet,h} + S_{wet,v} + S_{wet,f} + S_{wet,n}$$

Torenbeek

Form factors

- Aerodynamic surfaces

$$F_i = 1{,}34 \cdot M^{0{,}18} \cdot (\cos \Lambda_t)^{0{,}28} \cdot \left(1 + \frac{0{,}6}{x_t \cdot \bar{c}}(t/c) + 100(t/c)^4\right)$$

Sweep at maximum thickness position

maximum thickness position (as chord fraction)

- Fuselage

$$F_i = 1 + \frac{60}{\lambda_{fus}^3} + \frac{\lambda_{fus}}{400}$$

$$\lambda_f = \frac{L_f}{D_f}$$

- Nacelle

$$F_i = 1 + \frac{0{,}35}{\lambda_{nac}}$$

The friction coefficient is based on the boundary layer theory

- Laminar flow:

$$C_{f,i,lam} = \frac{1{,}328}{\sqrt{\mathrm{Re}_i}}$$

- Turbulent flow:

$$C_{f,i,turb} = \frac{0{,}455}{\left(\log_{10} \mathrm{Re}_i\right)^{2{,}58}\left(1 + 0{,}144 \cdot M^2\right)^{0{,}65}}$$

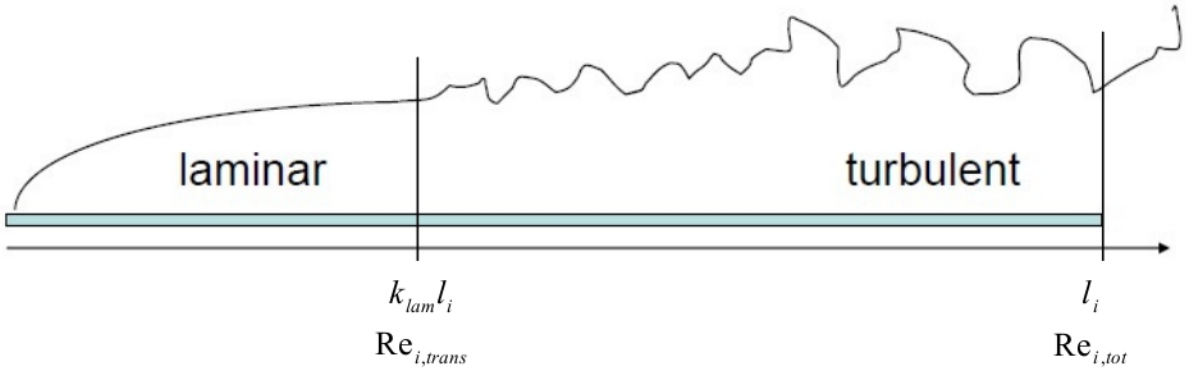
- Reynolds number:

$$Re_i = \frac{\rho \cdot V_\infty \cdot l_i}{\mu}$$

  - For aerodynamic surfaces, use mean aerodynamic chord
  - For bodies, use length

The friction coefficient is based on the boundary layer theory

- We can combine laminar and turbulent flow:

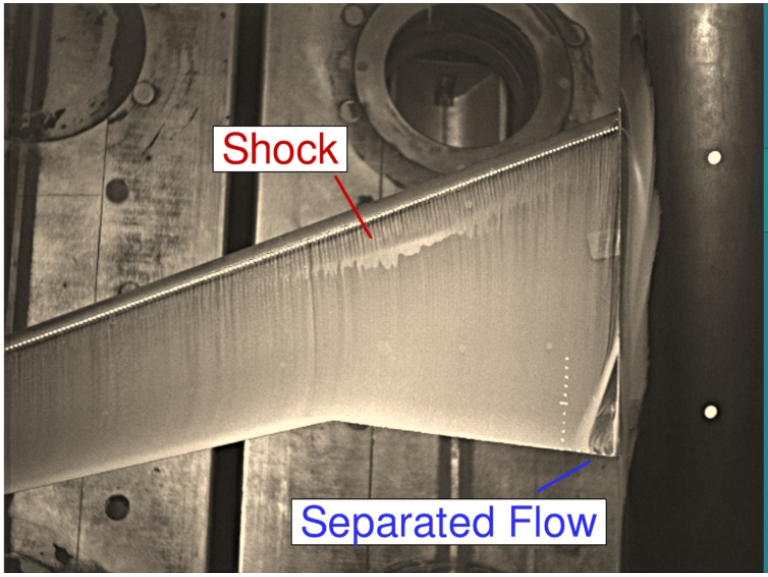


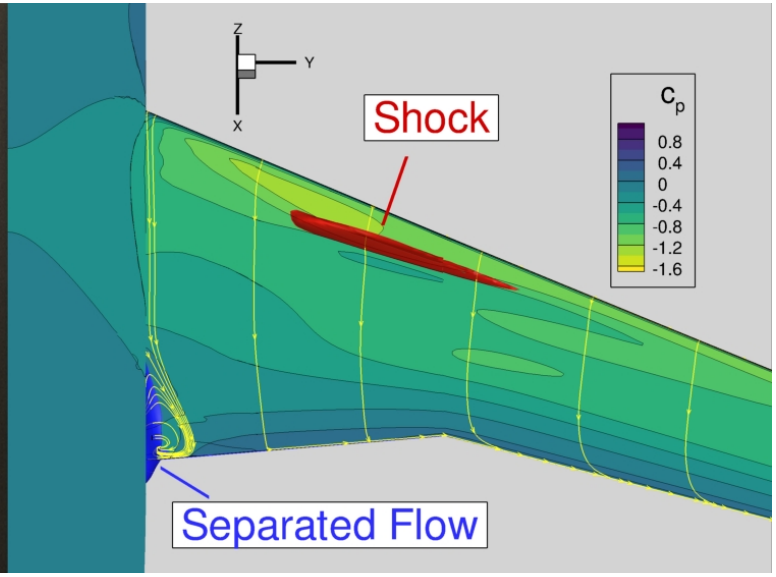
$$C_{f,i} = \left(C_{f,i,lam}\left(\mathrm{Re}_{i,trans}\right) - C_{f,i,turb}\left(\mathrm{Re}_{i,trans}\right)\right) \cdot k_{lam} + C_{f,i,turb}\left(\mathrm{Re}_{i,tot}\right)$$

k_{lam}: fraction of the length with laminar flow (0-1)

Interference factors

- Aerodynamic surfaces
  - With fairing: Q = 1.0
  - Low wing and no fairing: 1.1 < Q < 1.4
- Nacelles
  - Tangent to the fuselage: Q = 1.5
  - Less than 1 diameter away from fuselage: Q = 1.3
  - More than 1 diameter away from fuselage: Q = 1.0





Induced drag

- Highly dependent on wing planform and lift distribution.

$$C_D(C_L) = C_{D0} + KC_L^2$$

$$K = \frac{1}{\pi A e}$$

A: wing aspect ratio
$A = \frac{b^2}{S}$
Indicates how slender is the wing

$\boldsymbol{e}$: Oswald's efficiency factor
$0.80 < e < 0.90$
Indicates how far the current lift distribution is from the elliptical lift distribution

Induced drag

- Highly dependent on wing planform and lift distribution.

$$C_D(C_L) = C_{D0} + KC_L^2$$

$$K = \frac{1}{\pi A e}$$

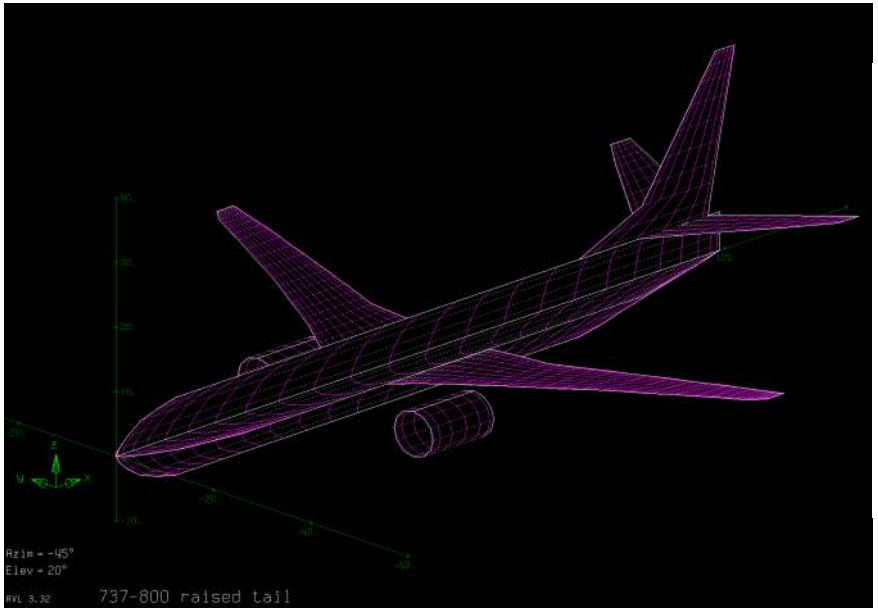
$$f_\lambda = 0.005 \cdot (1 + 1.5 \cdot (\lambda_w - 0.6)^2)$$

$$e = \frac{1}{(1 + 0.12 \cdot M^6) \cdot \left(1 + \frac{0.142 + f_\lambda \cdot AR_w \cdot (10 \cdot (t/c)_w)^{0.33}}{(\cos \Lambda_w)^2} + 0.1 \cdot \frac{3 \cdot n_{eng,w} + 1}{(4 + AR_w)^{0.8}}\right)}$$

Howe

Induced drag

- Lifting Line, Vortex Lattice (AVL) and Panel Codes (PANAIR) are also options



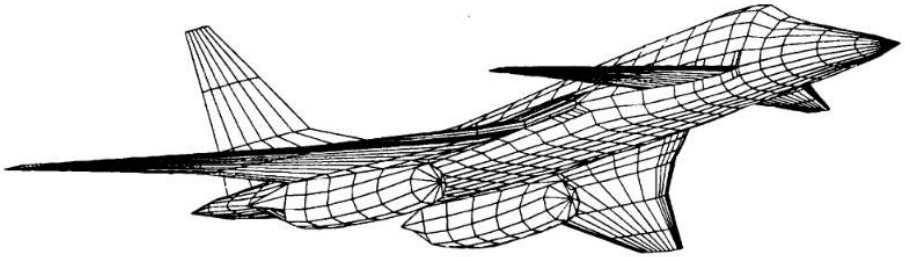


Figure 21.– PAN AIR model of supersonic fighter concept.

Erickson

Características do aerofólio são determinantes para a máxima sustentação da asa

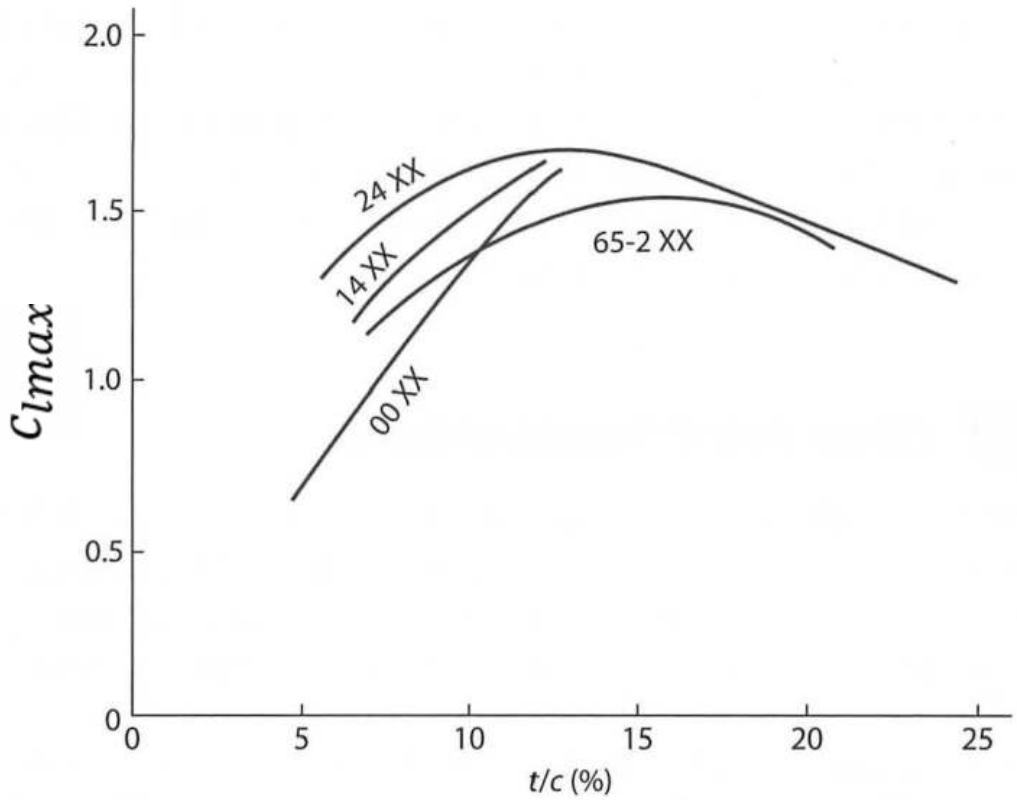


Fig. 4.13 Effect of t/c on maximum lift.

$$C_{Lmax} = 0.9 c_{lmax} \cos(\Lambda_{c/4})$$

wing airfoil

Raymer

Depois aplicamos incrementos de C_{Lmax} dependendo do hiper-sustentador

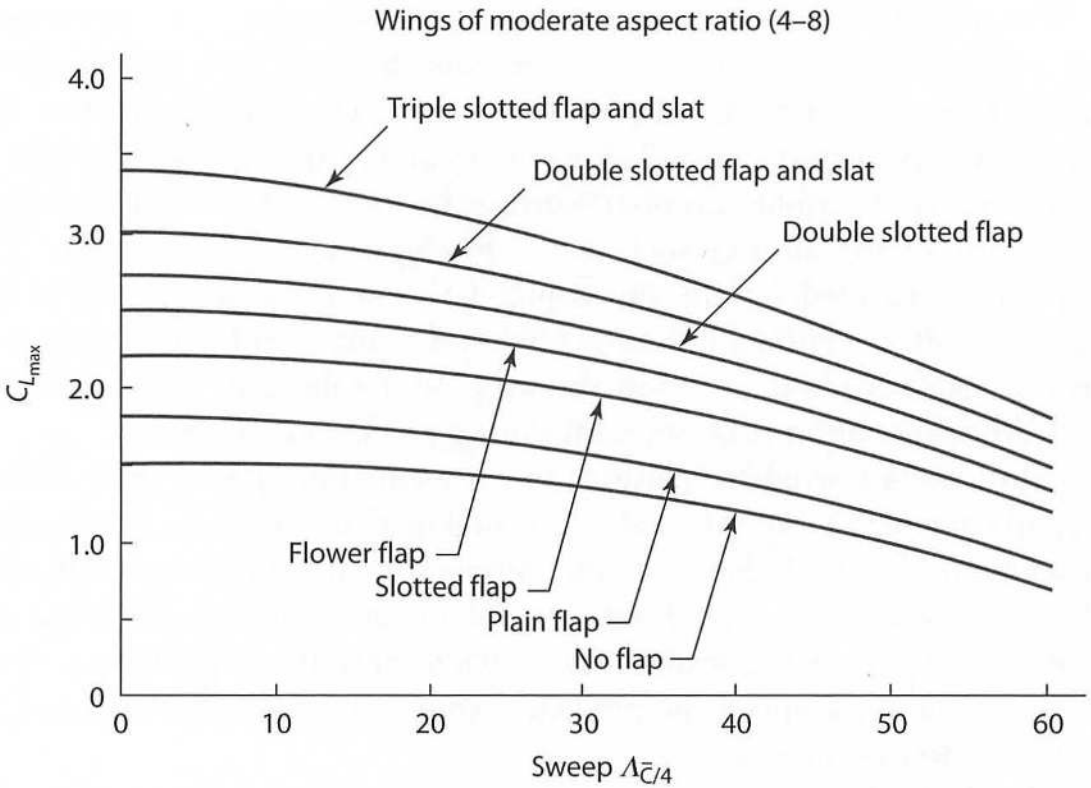
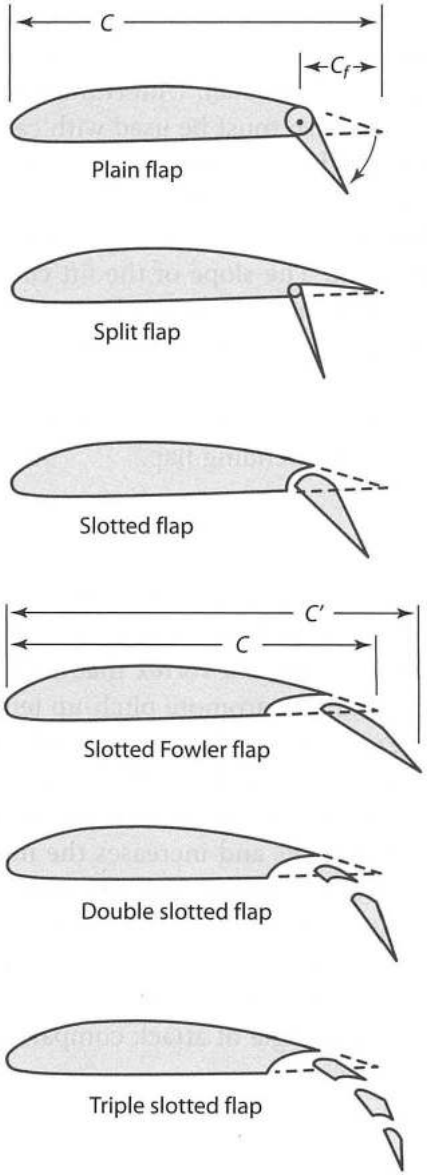
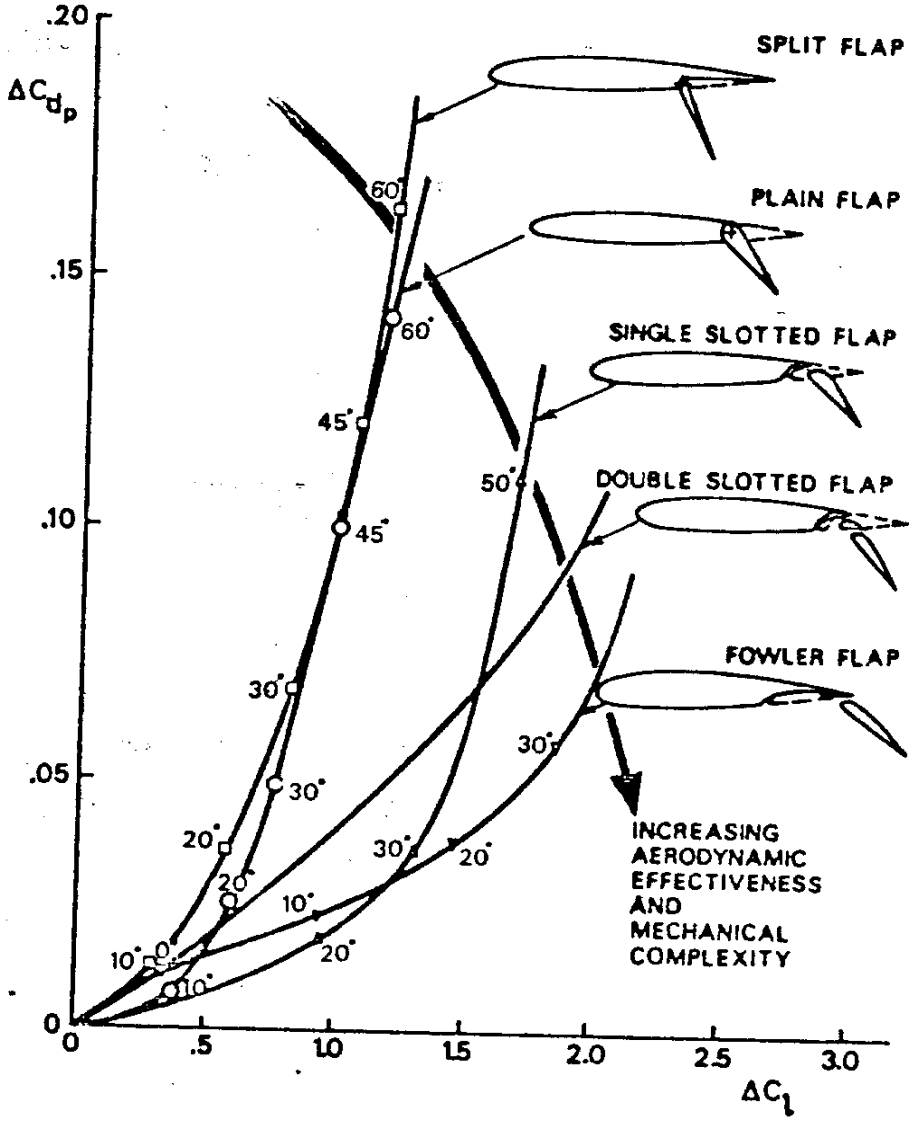


Fig. 5.3 Maximum lift coefficient.



Raymer

High-lift devices modify lift and drag



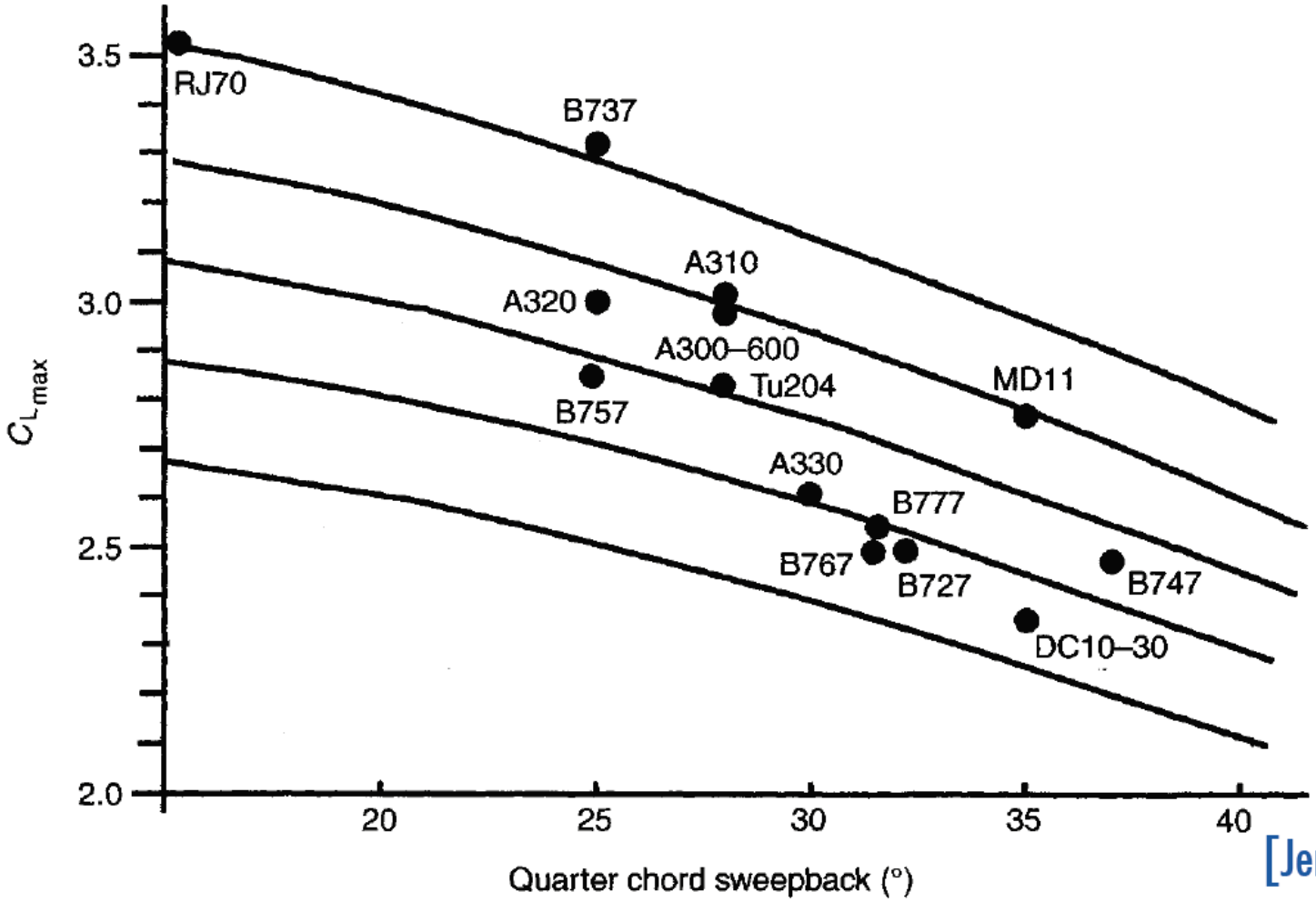
Valores típicos de deflexões

HIGH-LIFT DEVICE		TYPICAL FLAP ANGLE		$C_{L_{max}}/\cos\Lambda_{.25}$	
TRAILING EDGE	LEADING EDGE	TAKEOFF	LANDING	TAKEOFF	LANDING
PLAIN	-	20°	60°	1.40-1.60	1.70-2.00
SINGLE SLOTTED	-	20°	40°	1.50-1.70	1.80-2.20
FOWLER*	-	15°	40°	2.00-2.20	2.50-2.90
DOUBLE SLOTTED**	-	20°	50°	1.70-1.95	2.30-2.70
	SLAT			2.30-2.60	2.80-3.20
TRIPLE SLOTTED**	SLAT	20°	40°	2.40-2.70	3.20-3.50

* SINGLE SLOTTED

** WITH VARYING AMOUNTS OF CHORD EXTENSION (FOWLER MOTION)

Notes on Values for $C_{L_{max}}$



[Jenkinson]

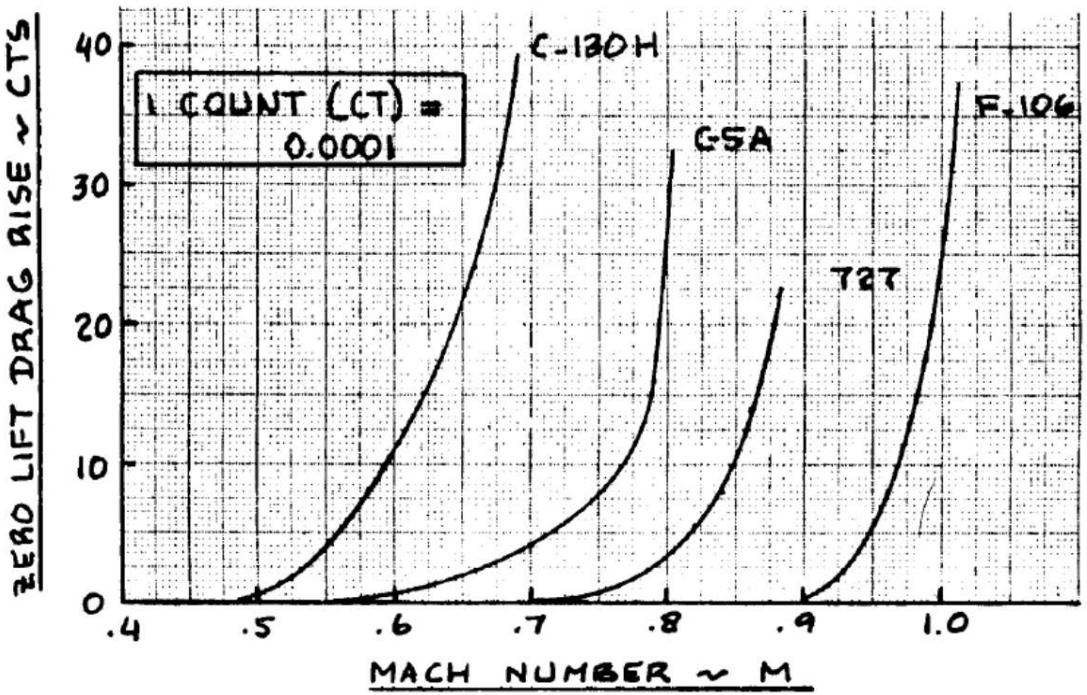
Typical Values for $C_{L_{max}}$

[Roskam]

Airplane type	Cruise	Take-off	Landing
Homebuilt	1.2–1.8	1.2–1.8	1.2–2.0
Single-engine GA	1.3–1.9	1.3–1.9	1.6–2.3
Twin-engine GA	1.2–1.8	1.4–2.0	1.6–2.5
Agricultural	1.3–1.9	1.3–1.9	1.3–1.9
Business Jet	1.4–1.8	1.6–2.2	1.6–2.6
Twin Turboprop	1.5–1.9	1.7–2.1	1.9–3.3
Transport Jet	1.2–1.8	1.6–2.2	1.8–2.8
Jet Trainer	1.2–1.8	1.4–2.0	1.6–2.2
Jet Fighter	1.2–1.8	1.4–2.0	1.6–2.6
Military Cargo	1.2–1.8	1.6–2.2	1.8–3.0
Flying Boat	1.2–1.8	1.6–2.2	1.8–3.4
Supersonic Cruise Plane	1.2–1.8	1.6–2.0	1.8–2.2

Wave drag

- Critical Mach Number :
  - Airflow somewhere over the airfoil reaches the speed of sound
- Divergence Mach Number:
  - Speed beyond which wave drag increases rapidly
  - Boeing definition: increase of 0.002 counts



Roskam

We can use the Korn equation to estimate wave drag

- Divergence Mach Number:

0.95 for supercritical airfoils, 0.87 otherwise

$$M_{dd} = \frac{0.95}{\cos\Lambda_w} - \frac{(t/c)_w}{(\cos\Lambda_w)^2} - \frac{C_L}{10\cdot(\cos\Lambda_w)^3}$$

- Critical Mach number:

$$M_c = M_{dd} - \left(\frac{0.1}{80}\right)^{1/3}$$

- Wave drag (M > Mc):

$$C_{D,wave} = 20\cdot(M - M_c)^4$$

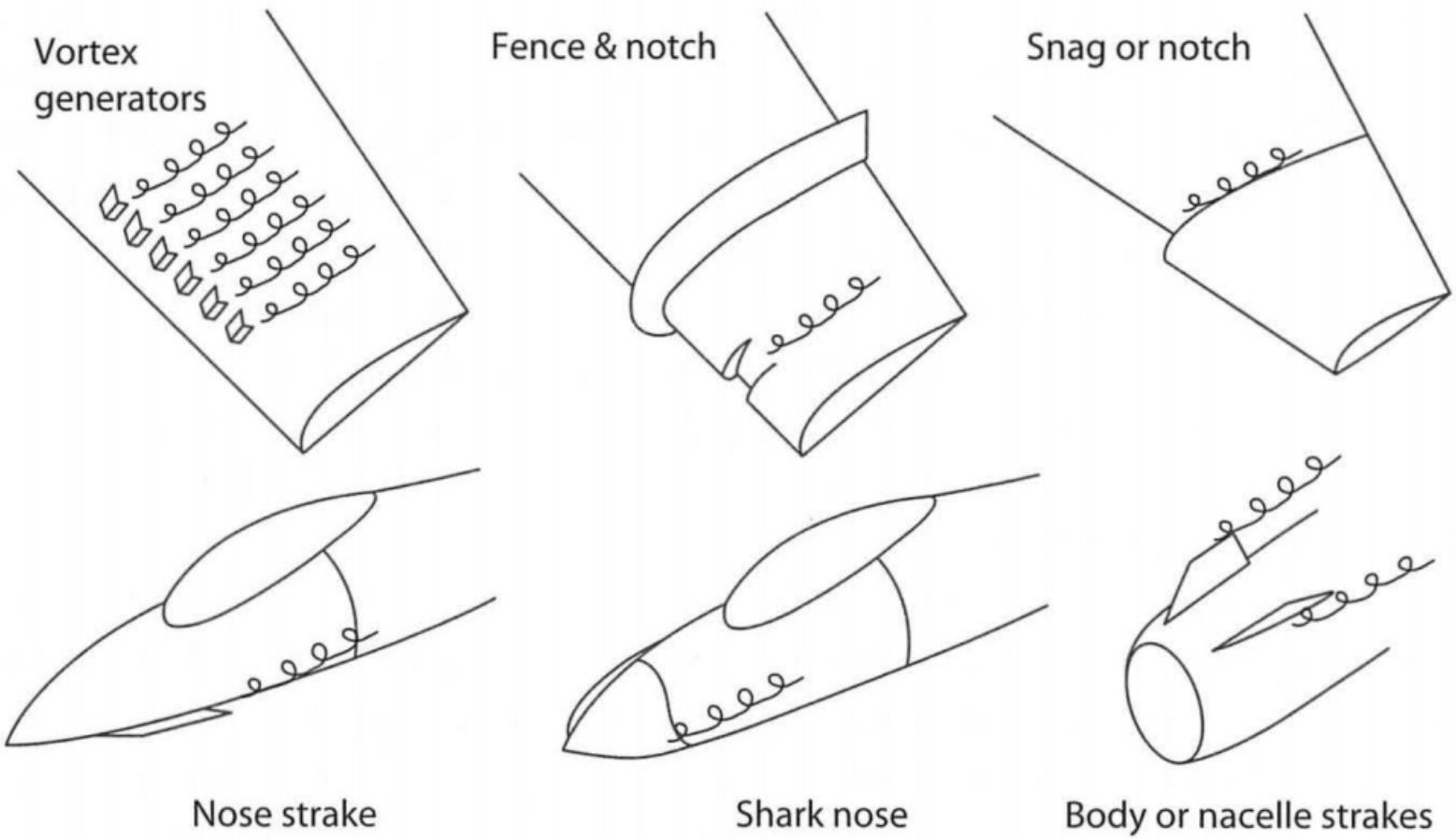
- Otherwise:

$$C_{D,wave} = 0$$

F-104

AR = 2.45 t/c = 3.36%

Design fixes



Design fixes

Phenom 100

aeroin.net

Design fixes

aviationtoday.com

ERJ-145

aslgroup.eu

Design fixes

AW.650 Argosy

wikipedia.org

Tarefa

- Seção 3.2.11 do roteiro
- Quiz até o dia 24/08/2021: https://forms.gle/Tqncr2mbCDThWjR57